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The Effect of a Three Set Tennis Match on Knee Kinematics and Leg Muscle Activation During the Tennis Serve

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THE EFFECT OF A THREE SET TENNIS MATCH ON KNEE KINEMATICS AND LEG MUSCLE ACTIVATION DURING THE TENNIS SERVE

by

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Abstract

THE EFFECT OF A THREE SET TENNIS MATCH ON KNEE KINEMATICS AND LEG MUSCLE ACTIVATION DURING THE TENNIS SERVE

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Tennis matches can be long, physically challenging affairs. Matches are often determined by the serving proficiency of the players. The serve has been extensively studied, but the relationship between the serve and match length regarding knee kinematics and leg muscle activation is not well documented in a real time environment. The purpose of the current study was to determine the effect a three-set tennis match had on knee kinematics and muscle activation of quadriceps and hamstrings during the serve. Ten male collegiate tennis players (age: 19.6±1.7) were recruited from The University of Texas at Tyler. All participants played a three-set match and digital video recordings and electromyography (EMG) readings of the first five serves (Test 1) and last five serves (Test 2) from each set were taken. Motion capture analysis was performed to calculate knee flexion and angular velocity. EMG analyses of selected muscles were performed through root mean square (RMS) and median power frequency (MPF). Significant test differences were seen in knee flexion and RMS values for the *biceps femoris*. Set differences were observed for the RMS values of the *rectus femoris* and both the RMS and MPF values of the *biceps femoris.* Additionally, a set by test interaction for the RMS of the *rectus femoris* was observed. Knee flexion results are consistent with previous studies which have shown that decreasing knee flexion has a detrimental effect on the serve and can cause a reduction in efficiency to occur as well. Recommendations to coaches would be to cue the players in on their legs during the serve when a decrease in proficiency occurs during a match.

Chapter One

Introduction

Tennis is a dynamic sport that combines components of endurance, flexibility, strength and power. Players must be able to play with repetitive bursts of speed and power for several hours at a time. Grand slam matches (those played at the 4 most prestigious tournaments) are the best 3 out of 5 sets; and can last hours and even days as shown by the record length 2010 Wimbledon match between John Isner and Nicolas Mahut, which lasted eleven hours and five minutes and took three days to complete. This match time is obviously not typical, but the average match time during 3-out-of-5 matches at grand slams is still two hours long (Hornery, Mujika, Mujika, & Young, 2007). The 2012 Australian Open Final between Novak Djokovic and Rafael Nadal is another good example of a long and decidedly fatiguing tennis match. This match set the record for the longest grand slam final at 5 hours and 53 minutes.

The game of tennis has changed since the Open Era began in 1968, with both the game and the individual players becoming faster with each generation. Equipment technology such as better string and racquet materials has been a contributing factor to the speed of play. In 1997 Mark Philippoussis held the record for the fastest serve at 142 mph. Just fifteen years later the record has increased to 163 mph. This was attained by Samuel Groth during the 2012 Busan Open Challenger (ATP World Tour, 2012).[1] These dramatic changes in the game have had the effect of requiring players to be quicker and more powerful in their play.

Better serves among today's players of all ability levels have helped contribute to long match times. Average serve speed has been increasing at all grand slam tournaments over the past twenty years. However, this has not led to greater inaccuracies and double faults as one might suspect. In fact, along with the increase in serve speed, there has been an overall decline in double faults over the past twenty years (Cross & Pollard, 2009).

It is clear that the serve, and more importantly holding serve, is paramount to success in tennis. Many professional men's matches are decided by only one break per set. Perhaps the best example of this is the 2009 Wimbledon final where Andy Roddick lost to Roger Federer 16-14 in the fifth set (which also reinforces the point made earlier: tennis matches can indeed be very long affairs). The only time Roddick was broken the entire match was in the very last game.

During a tennis serve, the body acts as a kinetic chain with four common points: a) the leg and hip section requires some knee flexion for cocking which provides the upward linear momentum when extension occurs, b) the trunk and scapula rotate and retract to allow the shoulder and arm to be cocked, c) the shoulder must externally rotate and horizontally abduct to achieve this cocking

[1] The fastest second serve on record is 144 mph which makes it faster than the overall record set by Philippoussis in 1997. Ivo Karlovic is the record holder for this achievement.

and then internally rotate for acceleration, d) finally, the forearm must pronate to accelerate the racket through the hitting zone: “Efficient use of the segments creates a racket velocity that is much more than the sum of its parts” (Kibler & Van der Meer, 2001).

Many studies have been conducted looking at various aspects of the serve due to the great importance placed on this one shot. Much of the research is biomechanical in nature and provides great insight into what actually happens during the crucial phases of the serve. When beginning the service motion the player will generally flex their knees before powerfully pushing up towards the ball. The legs require some degree of knee flexion during the backswing phase of the serve so that knee extension can generate large amounts of linear and angular momentum. This knee flexion is necessary before extension in order to execute the serve regardless of performance level (Girard, Micallef, & Millet, 2007). Servers who exhibit effective leg drives are more able to achieve near maximum velocity for the downward movement of the racket as the hip reaches its maximum vertical velocity (Elliott, Marsh, & Blanksby, 1986). While the extent of knee flexion is difficult to see in real time it is plain that the knees flex a considerable amount during the initial phases of the serve. Additionally the back leg of the server (this is the right leg for right-handed servers) provides most of the forward and upward push while the front leg provides a stable post for rotational movement (Bahamonde, 2000; Girard, Micallef, & Millet, 2005). Girard, Micallef, and Millett also showed that an effective leg drive with correct trunk rotation during the backswing phase increases serve efficiency in driving the racket down, behind, and away from the back which lengthens the trajectory of the racket to the ball (2005). When servers are not allowed to utilize their legs the serve speed is decreased when compared to their normal serve even though the peak anterior forces about the shoulder and the rate at which that force is developed are the same (Reid, Elliott, & Alderson, 2008). In *Mastering the Kinetic Chain*, it is stated that the legs are the start of the kinetic chain that culminates in the racket impacting the ball. The legs and trunk develop the largest portion of kinetic energy or force, and they are also the most common places for kinetic chain breakage to occur. This chain converts linear momentum to angular momentum around the stable post leg- this is the left leg for right-handed servers (Kibler & Van der Meer, 2001). In total, the legs and trunk develop 51% of the kinetic energy in the serve (Kibler, 1995, as cited in Kibler & Van der Meer, 2001). If a body segment drops out of this kinetic chain the force to make the racquet accelerate is decreased and large strains are placed on the surrounding segments.

Weakened leg muscles hamper the serve by causing a decrease in force production. During the early phases of the serve the knees and hips both flex with the hamstring and quadriceps muscles undergoing an eccentric contraction. The knees and hips must then extend to start off the kinetic chain. This upward push by the legs is the result of a forceful concentric contraction by the hamstring and quadriceps muscles. While muscle activation of the lower leg has obviously been extensively studied using electromyography, the activation of these muscles with regards to the serve has not been an area of extensive study. The majority of EMG articles dealing with the serve have concentrated on the upper body such as the shoulder (Kibler, Chandler, Shapiro, & Conuel, 2007), elbow (Morris, Healy, Pink, Perry, & Jobe, 1989), and trunk (Chow, Shim, & Lim, 2003; Chow, Park, & Tillman, 2009). If the leg muscles do not contribute enough force, then added strain will be placed on the other parts of the body. When dealing with weakened legs muscles the server will often try to maintain velocity by changing from an efficient push-through movement with the legs to a pull-through movement using the trunk and arm muscles (Kibler & Van der Meer, 2001).

The importance of the serve in tennis, and the importance of the legs in the serve are quite clear. One question that arises about the serve is: What happens to the biomechanics of the serve when one plays the type of long, fatiguing matches such as those played today? The literature has many studies dealing with fatigue in tennis, but unfortunately the scope of the studies does not often include the biomechanical aspects of the sport (see chapter 2).

In Hornery, Farrow, Mujika, and Young's review, *Fatigue in tennis,* which critiqued the current body of literature dealing with fatigue, it was concluded that a lack of sensitivity of the selected performance measures were an underlying constraint in all the studies. Due to these constraints, research should include more sensitive process based measures such as stroke kinematics rather than simply observing outcome measures such as velocity and accuracy. It was noted of a study done by Davey, Thorpe and Williams (2002) that, "the chosen protocols to induce fatigue and the decision to measure only motor-skill proficiency limited the generalisation of the findings" (Hornery et al., 2007, p.

202). For studies that wish to induce fatigue as part of the overall experiment, match equivalent fatigue (i.e. playing actual matches or using protocols that closely resemble the physiological nature of tennis) should be utilized instead of volitional exhaustion (i.e. using a protocol that declares fatigue has been achieved after so many missed forehands in a row or a set level of blood lactate accumulation has been reached) (Hornery et al., 2007). It also appears that when physiological strain is present during fatigue studies, stroke accuracy for groundstrokes is largely maintained, but a decrement in stroke velocity is often seen (Ferrauti, Pluim, & Weber, 2001).[2] Therefore, due to the constraints of using volitional exhaustion as a means of inducing physiological strain on participants, research concentrating on fatigue should focus on fatigue as induced by match play and measure precise process based outcomes (Hornery et al., 2007).

Purpose

The current study will focus on the legs, specifically quadriceps muscle activation and knee kinematics. If there is an effect on the serve as a result of playing three sets, then we can be reasonably sure that effect will present itself in the legs since, as it has already been noted with Kibler and Van der Meer, kinetic chain breakage often occurs in the legs (2001). Therefore it is the purpose of this study to determine the effect a three-set tennis match has on quadriceps and hamstring activation and knee kinematics during the serve of collegiate male tennis players.

[2] The reasons for this are not completely understood, but Hornery et al. postulates this could be due to players reducing stroke speed in order to increase accuracy which is supported by Fitts speed-accuracy trade-off theory (Fitts, 1954).

Hypothesis and Specific Aims

It is believed that the greatest fatigue-induced breakage in the kinetic chain occurs in the legs during the serve in tennis.

Specific Aim 1: Identify the muscle activation pattern of the quadriceps (*rectus femoris*) and hamstring (*biceps* femoris) muscles during the tennis serve when a three-set match is played. The working hypothesis is that throughout the course of a tennis match, the muscle activation will be reduced.

Specific Aim 2: Identify the kinematic pattern of the knee joint during the tennis serve when a three-set match is played. The working hypothesis is that one or both of the kinematic variables (knee flexion angle and angular velocity) will be reduced.

Chapter Two

Expanded Review of Literature

Overview

When looking at the serve, the differences seen in velocities between first and second serves comes from changes in ball location and impact locations which increase the spin on the ball. Greater spin will increase accuracy since this causes the ball to drop quicker due to the *Magnus effect*. New string technology has contributed to increasing spin on the ball which has provided a positive contribution to the effectiveness of the modern serve. When looking at the physiological side of tennis, blood lactate is a poor predictor of performance and the aerobic aspect is often overrated due to the intermittent nature of the sport. Finally, when observing electromyography and fatigue, it is known there is a frequency shift to the left when dealing with isometric contractions, but the expected outcome is not known when dealing with the dynamic contractions of a tennis serve.

Literature Review

It is well known that second serves travel with less velocity than first serves; this however is not due to a decrease in pre-impact racket speed. Servers instead change the location ball and impact locations. Observations of serve kinematics indicate that forward displacement of the ball toss for the first serve is greater than for the second serve. This change along with an increased pre-impact vertical and lateral racket velocity result in a more consistent serve. Thus the speed-accuracy trade-off of the ball does occur but not the racket speed-accuracy trade-off (Chow, Shim, & Lim, 2003). Cauraugh, Gabert, and White had similarly interesting findings when observing first serves. The researchers had players strike their serves at 70%, 80%, and 90% of their maximum velocity. No significant differences for either accuracy or consistency were observed between any of the serve speeds. One reason put forward for the lack of differences in the serves was increasing spin imparted by faster swing speeds increased the spin on the ball helped maintain accuracy. Additionally faster swing speeds were postulated to decrease timing errors as defined by Schmidt (1988) which also helped maintain accuracy and consistency (Cauraugh, Gabert, & White, 1990).

It is obvious that spin plays a vital role in maintaining serve accuracy and consistency. An increase in serve velocity without a decrease in accuracy may initially seem counter-intuitive; however, the field of fluid mechanics can provide the reason for this occurrence. On any shot, including the serve, spin is placed on the ball. As the ball travels it interacts with the air around it. As the ball rotates it drags some of the fluid (air) around itself. This flow of air is not symmetrical around the ball; the average pressure is less on the lower half of the ball than on the upper half (this describes topspin, the opposite occurs when underspin or backspin is used). This phenomenon, known as the *Magnus Effect*, explains the interaction between the object, its spin, and the fluid it is traveling through

(Young, Munson, & Okiishi, 1997). It is the Magnus Effect which explains why a tennis stroke which applies large amounts of topspin to the ball causes it to rapidly drop. Often striking the ball harder is accompanied with an increase in spin. This helps explain the findings of Cauraugh, Gabert, and White with regards to serving speed and accuracy. As the players moved closer to their maximum racket velocity, they were increasing ball speed but also spin which had a net effect of zero with regards to accuracy and consistency.

Another factor having a major impact on tennis and serving is the change in the composition of tennis strings. Polyester string now dominate the professional tour with a majority of ATP and WTA professional players using these types of strings as well as many collegiate and recreational players (Garber, 2011). The polyester strings add even more spin to the ball which only enhances the Magnus Effect. The drastic changes in strings ultimately help explain the increased speed of the game, including the serve. As mentioned in Chapter 1 the serve has been increasing in speed over the past twenty years while double-faults have actually been decreasing (Cross & Pollard, 2009).

Another focus of research in tennis deals with the physiology of the game. Davey, Thorpe, and Williams used a protocoled fatigue test with the assistance of a tennis ball machine to induce their operational definition of fatigue. Their findings indicated that serving performance was negatively affected by the fatiguing protocol; however, as will be shown below, the validity of these findings has been called into question. While the above study focused on solely on fatigue, other studies have added the additional variable of supplementation to determine the best possible nutrition intake for optimal performance. Supplements such as carbohydrates and caffeine have been studied for their effects individually and working in concert with each other. Carbohydrates have been shown to provide performance benefits over placebos, but combining caffeine with the carbohydrate supplementation elicits no additional gains- these gains were measured by recording error rate, ball velocity, placement precision, etc. (Vergauwen, Brounds, & Hespel, 1998). In *A physiological profile of tennis match play*, the style of play exhibited had a great impact on energy demands. Depending on if one is a counterpuncher, aggressive baseliner, or serve-and-volley player; this will have a significant impact on energy needs. The aerobic capacity of players was thought to be sufficient to supply the body's energy needs without a great contribution from anaerobic mechanisms (Smekal, et al., 2001).

While the author of the current study does not dispute that playing style has an impact on energy demands there is some uncertainty regarding the claim that the aerobic supply is responsible for most of the bodies energy needs during a match. Christmass, Richmond, Cable, Arthur, and Hartman studied exercise intensity and metabolic response in singles and recorded heart rate percentage based on theoretical maximum to be 86.1± 1.0% during rallies and 82.8± 1.1% in between points (1998). The authors noted in their study that predictions of VO2 based on measurement of heart rate during play overestimate the aerobic response during intermittent exercise such as tennis. Additionally lactate determination can only reflect exercise intensity immediately before sampling (Christmass, Richmond, Cable, Arthur, & Hartmann, 1998).

The above findings would seem to contradict the conclusion of *A physiological profile.* Ferrauti, Pluim, and Weber reached the same conclusion in 2001 when they concluded blood lactate could be a poor predictor of sprint performance. The findings of Christmass et al. and Ferrauti, Pluim, and Weber also clash with some of Davey, Thorpe, and Williams' work which measured lactate concentration levels as high as 9.6$\pm$ 0.9 mmol while only 25% through their fatigue test. Taken together this information indicates that tennis has aerobic as well as significant anaerobic elements intertwined within the game.

As with any physical activity, tennis has a fundamental underlying muscular element that the current study will seek to examine. In order to study the inner workings of the human musculature electromyography is often the tool of choice. Electromyography provides information pertaining to the final control signal of each muscle and more importantly for the current study: EMG provides researchers with information on the state of fatigue of the muscle (Winter, 2009). Electromyography systems are able to detect information about the muscle because muscle tissue conducts electrical potentials which are known as motor unit action potentials. Electrodes placed on the surface of the skin record the potential transmitted along the muscle fibers at a given time. The pick-up zone for individual muscle fibers by an electrode depends on muscle fiber size and the number of fibers innervated by a motor unit. The larger each of these factors is, the greater the pick-up zone for a particular muscle will be (Winter, 2009).

Additionally, the distance apart the surface electrodes are placed from each other can have an effect on the interpretation of the signal. Electrodes placed closer together will give a reading of the specific muscle they are placed on. As the interelectrode distance increases the reading will move to a broader generalization of the surrounding region (Criswell, 2011). It was for this reason that the electrodes in the current study were placed closely together in order to gain information on the specific muscles studied and not the readings from the general region of the leg.

Chapter Three

METHODS

Overview

Ten subjects from the University of Texas at Tyler participated in this study. Kinematic analysis was done through the use of motion capture while muscle activation was measured using electromyography. The serve was observed at the beginning and end of each set of a three-set match. The EMG data were analyzed by taking the peak Root Mean Square and Median Power Frequency values for each serve. Kinematic data were obtained by the manual digitization of each serve. Statistical analysis was then conducted using a two level repeated measures of analysis of variance test for each variable.

Participants

The participants used for this study consisted of 10 males from The University of Texas at Tyler with an average age of 19.6 ± 1.7 years. Nine participants were current members of the university tennis team while the other participant was a former member of the team. Average height of participants was 178.5 ± 4.0 cm and average weight was 77.7 ± 7.5 kg. Institutional Review Board approval was granted by the University of Texas at Tyler (see Appendix A) and all participants were free from any risk factors as defined by the American

College of Sports Medicine’s Guidelines for Exercise Testing and Prescription and were therefore classified as a Class A: Apparently Healthy Individuals. All participants signed informed consent forms before testing (see Appendix A) which expressed exactly what would be required of them which included: playing three sets of tennis while being filmed, wearing reflective anatomical markers on their legs, and wearing a portable electromyography module. Additionally all participants had been cleared to practice and participate in intercollegiate athletics by The University of Texas at Tyler athletic training staff. All participants were right handed.

Instrumentation

Kinematic data were acquired through Casio high speed EX-FH25 cameras. Reflective anatomical markers in the form of 3M reflective tape were used to facilitate digitizing after the matches were complete. These markers were placed on three anatomical landmarks (greater trochanter, lateral femoral epicondyle, and lateral malleolus) of the server’s right leg. The cameras were placed adjacent to the fence of the back court, perpendicular to both baselines of the tennis court (Figure 1). Rectangular camera housings (Figure 2) which measured 91 centimeters high, 63 centimeters wide, and had a depth of 61 centimeters were placed over the cameras to protect them from any tennis balls struck at high speed which could have damaged the camera. A circular hole measuring 5.5 centimeters in diameter was cut from the camera housing to provide a slot for suitable viewing. This slot was 71 centimeters from the base of the camera box to the center of the slot. Vicon Motus 2-D software (Vicon, Centennial, Co, USA) was later used for the digitizing of each serve. Although the serve has actions in many planes, it was determined that 2-D analysis was appropriate for this experiment. During the flexion and extension phases of the serve, every participant brought their back leg into a plane parallel to the baseline and perpendicular to the camera thus allowing for accurate digitizing of the serve.

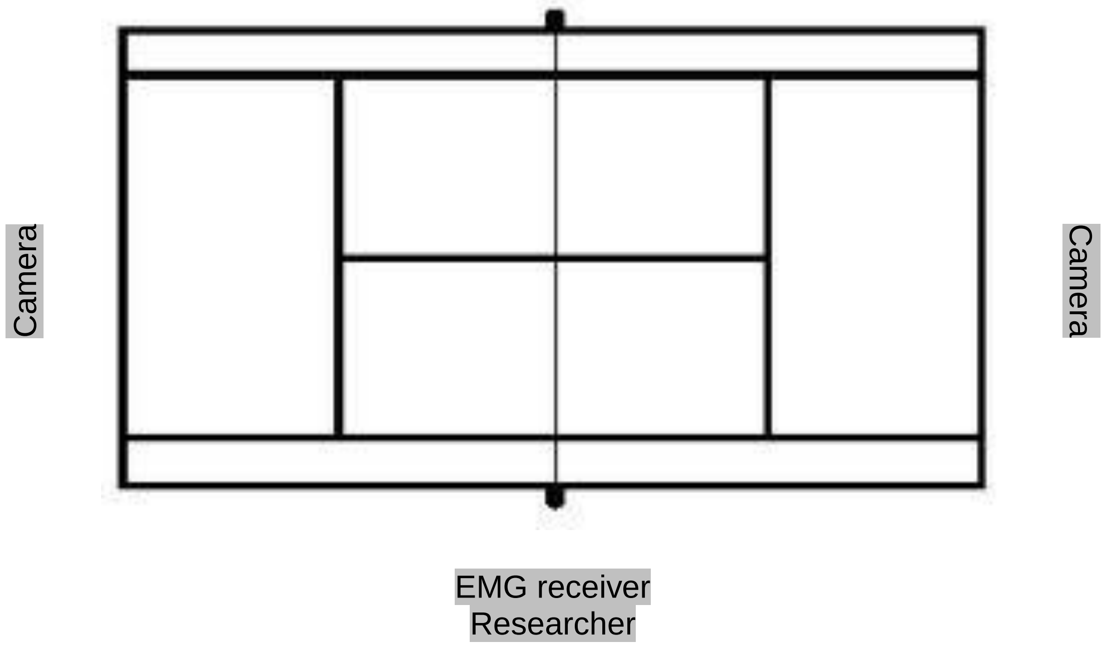

Figure 1. The court setup for each experiment. The cameras were placed behind each baseline while the researcher sat near the net post with the EMG equipment.

Data on muscle recruitment were attained through a wireless EMG system (BioNomadix Dual-channel, Biopac systems) instead of using traditional wired electrode leads (Figure 3). This allowed the participants to freely move around the entire court and play unhindered by any wires.

Figure 2. Camera protected by the camera housing.

The wireless system included the BioPac MP150 system and wireless BioNomadix modules. BioPac EL504 2.5 cm cloth electrodes were used for electromyography readings. These electrodes have a solid gel adhesive which helps in reducing movement artifacts by providing a cushion that absorbs electrode movement. Acqknowledge software v. 3.9 was used for acquisition and processing of the EMG signals.

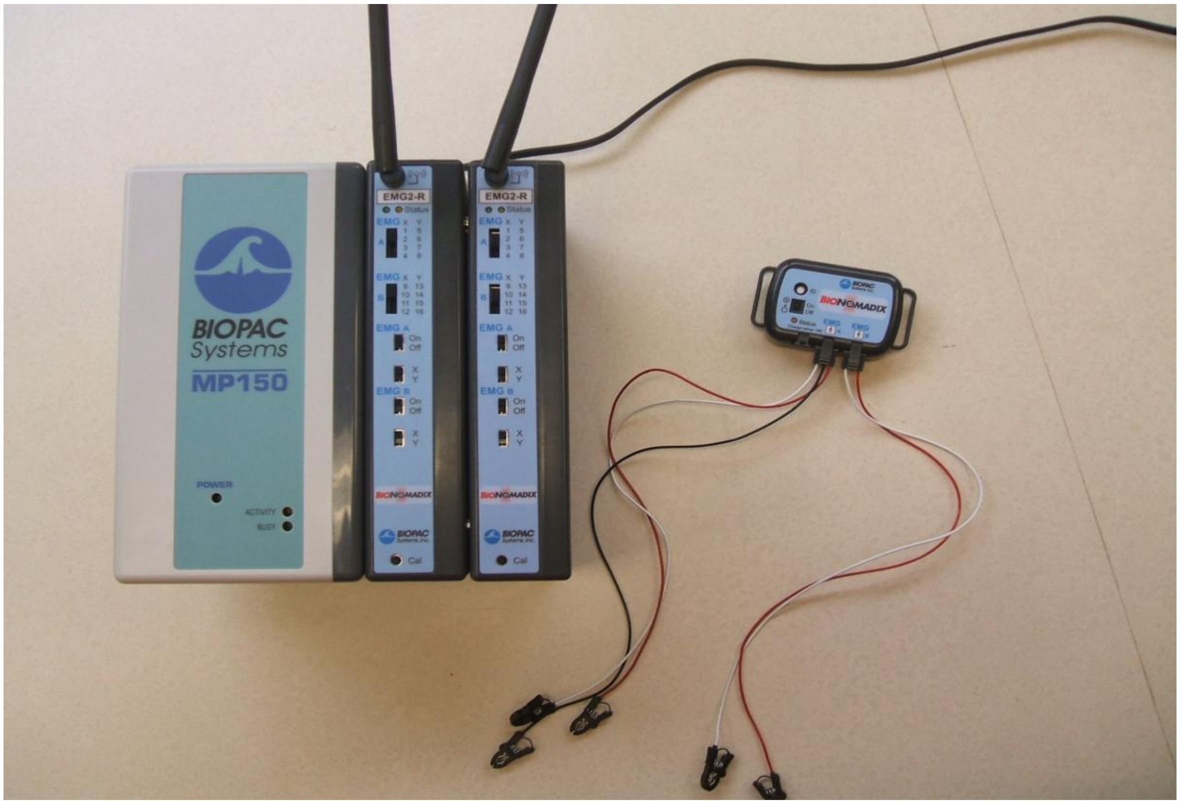

Figure 3. Biopac MP150 system, the wireless EMG amplifiers, and the wireless EMG module worn by the participants.

General Protocol

Before participating in the experiment, each participant read and signed informed consent papers. The participant's height, weight, and age were then recorded. After this electrodes as well as anatomical markers were placed on the subjects in the biomechanics lab of the University of Texas at Tyler. Prior to electrode placement the skin was cleaned using rubbing alcohol. Bipolar electrodes were placed over the muscle belly of the *rectus femoris* and *biceps femoris* on the participant's right leg (Figure 4). The distance between the superior aspect of the Ilium and the patella was measured and the midpoint between these two landmarks was used for electrode placement on the *rectus* femoris. For placement of the electrodes on the *biceps femoris* the distance between the inferior ramus of the ischium to the fibular head was measured and the midpoint then found.

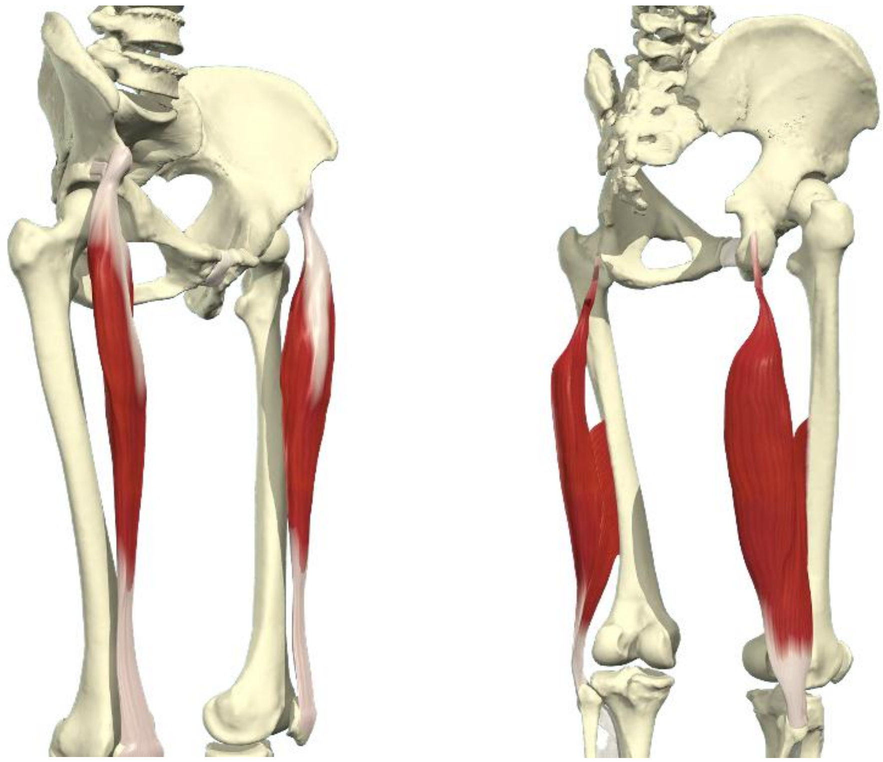

Figure 4. Rectus femoris and biceps femoris muscles. Pictured left is the anterior view of the rectus femoris muscle and right is the posterior view of the biceps femoris muscle.

Anatomical, reflective markers were placed on the right leg of the participant’s greater trochanter, lateral femoral epicondyle, and lateral malleolus The right leg was used since this was the back leg for all subjects during the serve and previous research has shown that the back leg provides the greatest upward push to the ball during the serve (Bahamonde, 2000; Girard, Micallef, and Millet, 2005). Afterwards, participants were taken to the university's tennis courts where they underwent a standard tennis warm-up of 10 minutes consisting of groundstrokes, volleys, overheads, and serves just as they would prepare for an actual match. The UT Tyler tennis team uses Wilson US Open Heavy Duty balls for matches, so these balls were chosen for use during the experiment. Before the warm-up began, participants were given three new balls to be used during the match. After the warm-up was complete and both participants signaled they were ready, play of a three-set match (Figure 5) then commenced.

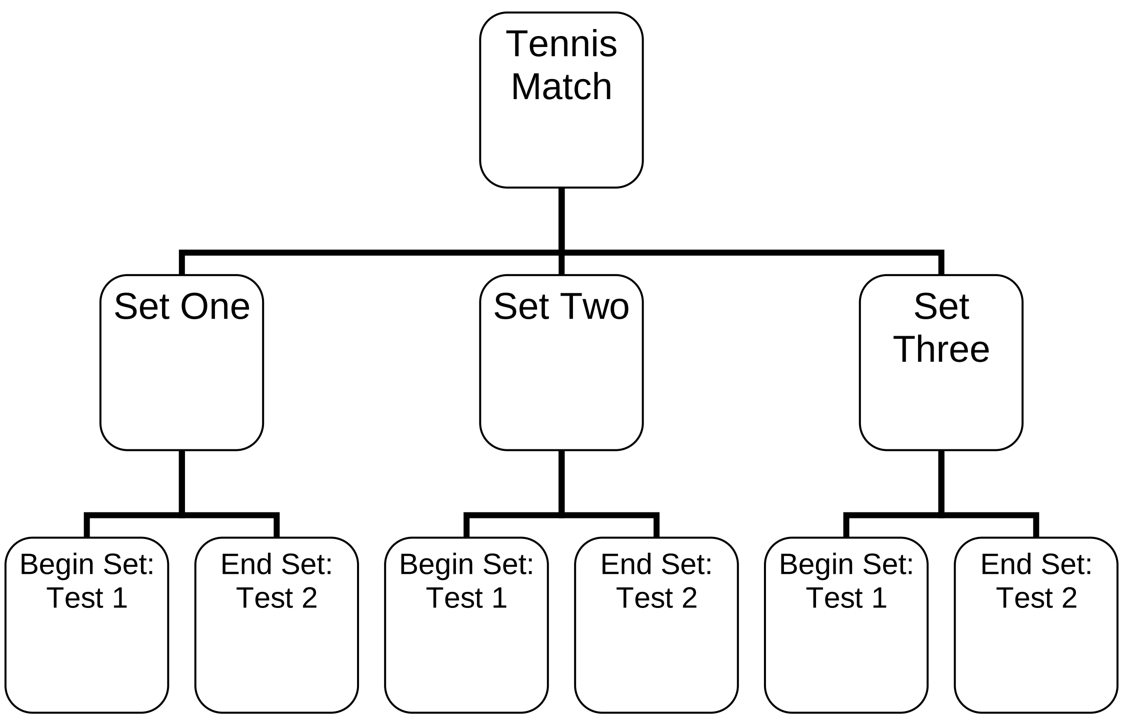

Figure 5. Experimental design. The layout of a 3-set match and all the times of measurement.

Effect of three sets on kinematics and leg muscle activation

The first five (test 1) and last five (test 2) serves of each set were recorded using both video and EMG for each participant. The final result was a three-set match with two tests per set and five trials per test. The five trials per set were then averaged for a final value for each test. Standard playing protocols were followed including the allotted time between points (30 seconds), changeovers (90 seconds), and sets (120 seconds). Each set was required to last at least 9 games as this was the average set length of the UT Tyler tennis team during the fall 2011 season.

EMG Data Collection and Analysis

The EMG data were recorded manually by the researcher for each serve. The Acqknowledge software was set to a sample rate of 1,000 samples per second. Separate channels were setup prior to the beginning of play that displayed both the raw EMG signal and the Root Mean Square (RMS). RMS is a common form of EMG rectification which entails squaring the data, summing the squares, dividing this sum by the number of observations, and then take the square root. The formula for this is shown here:

$$\{|m(t)|\} = 1/T\ [\int_{t}^{t} +^{t} m^{2}(t)\ dt]^{1/2} \qquad (1)$$

T is the time period of integration (Criswell, 2011).

The software was set to perform this function over every 100 samples meaning the RMS function did this calculation 10 times per second. Prior to the beginning of each serve to be recorded the researcher would start the EMG software just before the serve was initiated and the researcher stopped the software after the serve had been struck. The graph of the serve was then immediately saved and the software was readied for recording of the next serve. This was done for the first five serves of each set and for the last five serves of each set. Every participant received this treatment with regards to EMG collection of serves.

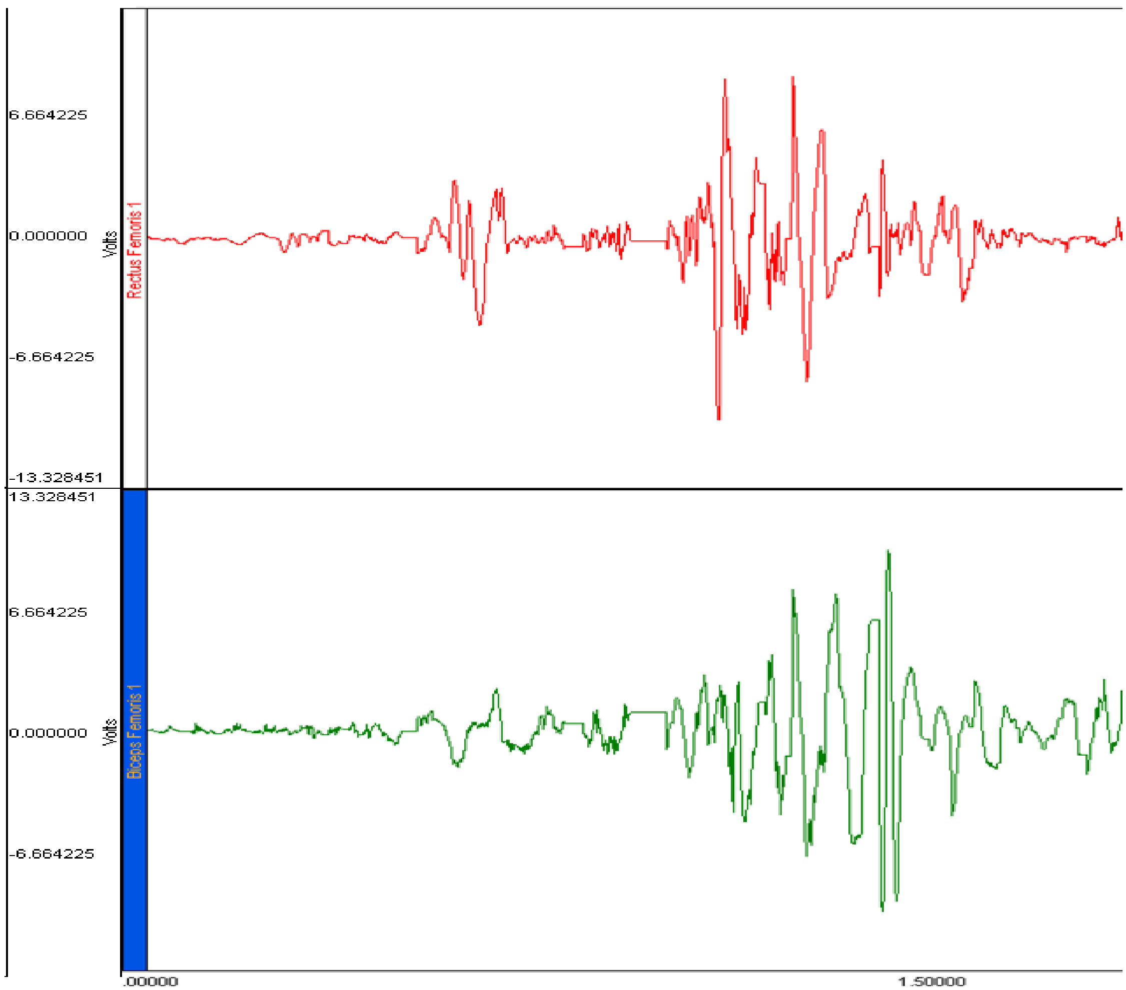

Figure 6. The raw electromyography signal. Top signal is the rectus femoris, bottom signal is the biceps femoris. Units for vertical axis are millivolts. Units for horizontal axis are seconds.

The peak values of the Root Mean Square for each serve were collected along with Median Power Frequency (MPF) analysis. MPF was established to determine if any shift in frequency occurred in the muscle fibers. In order to do this analysis, several transformations of the raw EMG signal (Figure 6) had to be undertaken. First the raw EMG graph of the signal was transformed using the power spectral density analysis (PSD) function (Figure 7).

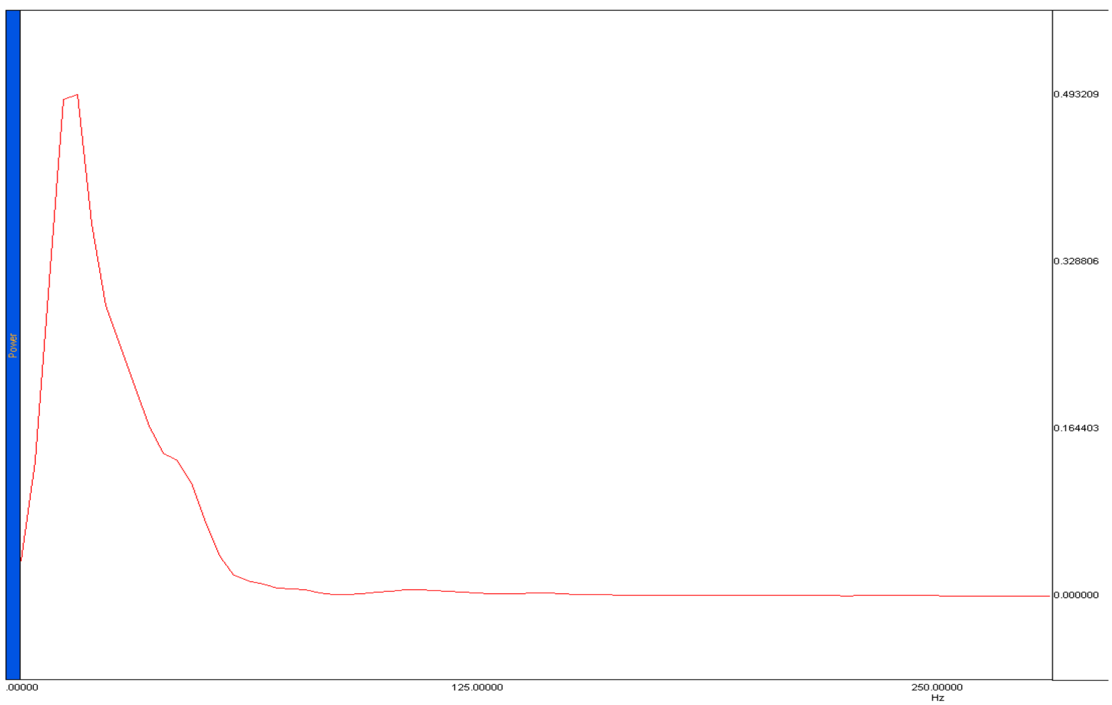

Figure 7. The Power Spectral Density of the raw EMG graph. Units for vertical axis are watts per hertz (V^2/Hz). Units for horizontal axis are hertz.

The integral of this PSD graph was then taken which allowed for the last step in the process. This final step involved the graph once again being transformed using the waveform math function. In order to perform this operation the graph is divided by the constant (K) which is the maximum value of the integral graph (Figure 8). Median Power Frequency was used because it had the advantage of not needing each subjects EMG readings be normalized to a voluntary contraction, and MPF has been shown to provide reliable and consistent data with regards to muscle fiber conduction velocity (Basmajian & De Luca, 1985). The mathematical formula for Median Power Frequency appears as such:

$$\int_0^{fm} X^2\,(f)\,df = \int_{fm}^{\infty} X^2\,(f)\,df = \frac{1}{2}\int_0^{\infty} X^2\,(f)\,df \tag{2}$$

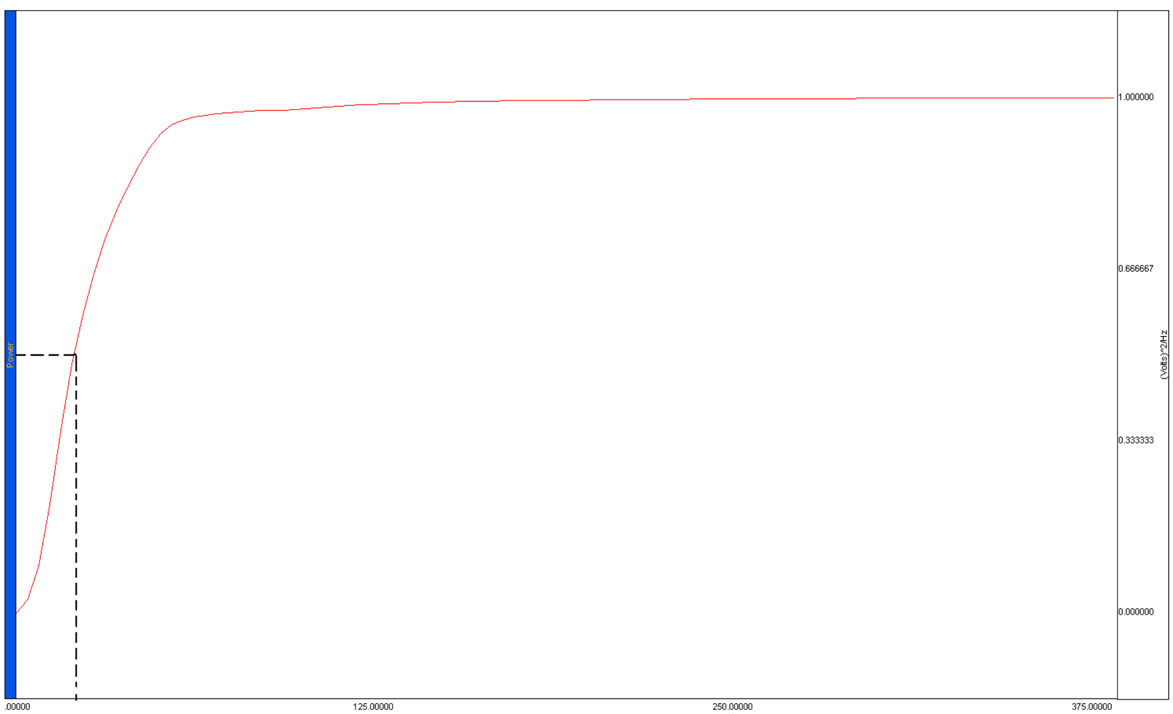

Figure 8. Median Power Frequency graph. The intersection of the dashed line indicates where the Median Power Frequency value lies. Units for vertical axis are watts per hertz (V^2/Hz). Units for horizontal axis are hertz.

Kinematic Data Collection and Analysis

Due to the large amount of storage space needed for saving the video recordings the cameras were only set to record during the beginning and end of each set. When a series of serves was to be measured the camera adjacent to the server was set to record. After all serves had been recorded for that portion of the set, the camera was then shut down and the video was immediately downloaded to the researcher's computer. Every time the camera was turned on to collect data on serves a new calibration frame was taken to ensure later accuracy when the videos were to be digitized. The calibration object measured 33cm by 32cm and was placed just to the left of the baseline center mark in the same plane the participants occupied when serving.

Upon completion of testing, all videos were manually digitized using Vicon Motus 2D software v. 8.5. Each serve was digitized from the beginning of knee flexion to the point of full knee extension (Figure 9). A template was created before any digitizing took place that included the spatial model of the serving leg, the camera setup, and the size in centimeters of the calibration object that was used. Each calibration frame had to be digitized along with every individual serve digitized since as mentioned earlier, a new calibration frame had to be taken for each of the six different times of measurement. Maximum Knee flexion and angular velocity data were then taken for each trial.

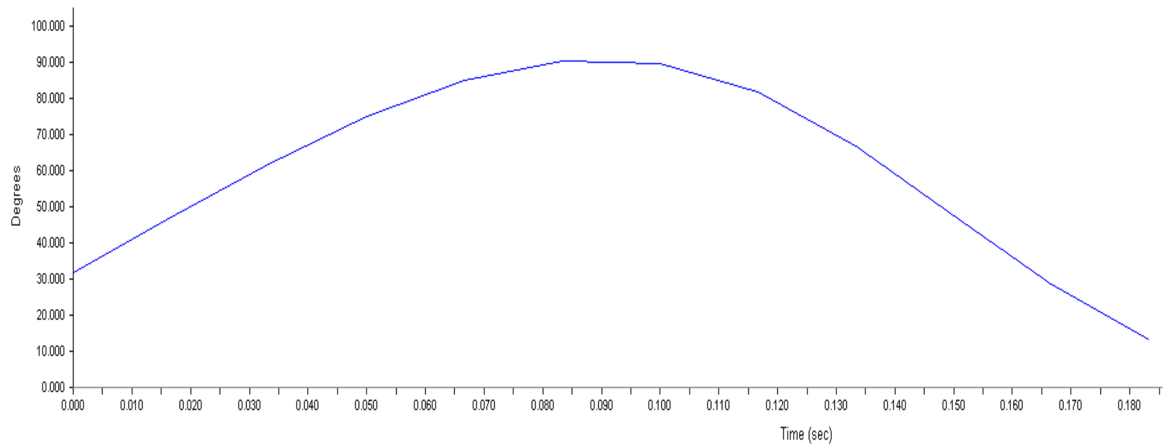

Figure 9. Knee flexion graph of the serve. Units for vertical axis are degrees. Units for horizontal axis are seconds.

Statistical Analysis

Significance level was set *a priori* to 0.05 before testing began. A two level (Set x Test) repeated measures analysis of variance tests were run using SPSS software on the kinematic variables of knee flexion and angular velocity of the knee as well as the electromyography data. Assumptions of sphericity for each data set were established before further analysis. If assumptions of sphericity were not met then Greenhouse-Geisser corrections were used. *Post* hoc analysis was run using Least Significant Difference. Effect size was calculated using partial eta squared. Effect size for significant differences within sets or tests was calculated using Cohen's *d* test. *Post hoc* power analysis for all significant statistical tests was conducted using G*power for kinematic and EMG data (Faul, Erdfelder, Lang, & Buchner, 2007).

Chapter Four

Results

Overview

With regards to knee flexion, ANOVA tests revealed significant test differences within each set (beginning and end of each set), but no differences between sets. No differences for any times of measurement were seen for knee angular velocity. For the *rectus femoris*, significant differences were observed in the RMS between sets and for a set by test interaction. The *biceps femoris* had significant differences between sets and also between tests for RMS values. Additionally, for the *biceps femoris,* when taking median power frequency into consideration, significant differences were revealed between sets.

Knee Kinematics

Knee flexion. No significant differences in knee flexion were seen between sets, $F(2,7) = 2.27$, $p = .132$. There was a significant difference between tests, $F(1,8) = 9.20$, $p = .014$, $\eta^2 = .505$. The *post* hoc power analysis indicated the sample of 10, with and alpha of .05 and a small effect size provided power of .78. The bar graph below (Figure 10) shows the differences in tests for each set. Pairwise comparisons showed that the beginning of each set (test one; $M = 76.04^{\circ}$, $SD = 12.54$) was greater than the end of each set (test two; *M* = 72.87º, *SD* = 13.82). Between tests effect size was *d* = .24. No significant interaction was seen between sets and test, $F(5,4) = 0.25$, $p = .78$. Table 1 gives the mean and standard deviation for all time of measurement for knee flexion.

Knee Flexion

Table 1. Average knee flexion for each set and test. Values are in degrees (n=10).

	Beginning of Set	End of Set
	Mean ± S.D.	**Mean ± S.D.**
Set 1	76.96±10.66	73.96±15.23
Set 2	77.04±12.45	74.57±13.27
Set 3	74.11±13.48	70.09±11.60

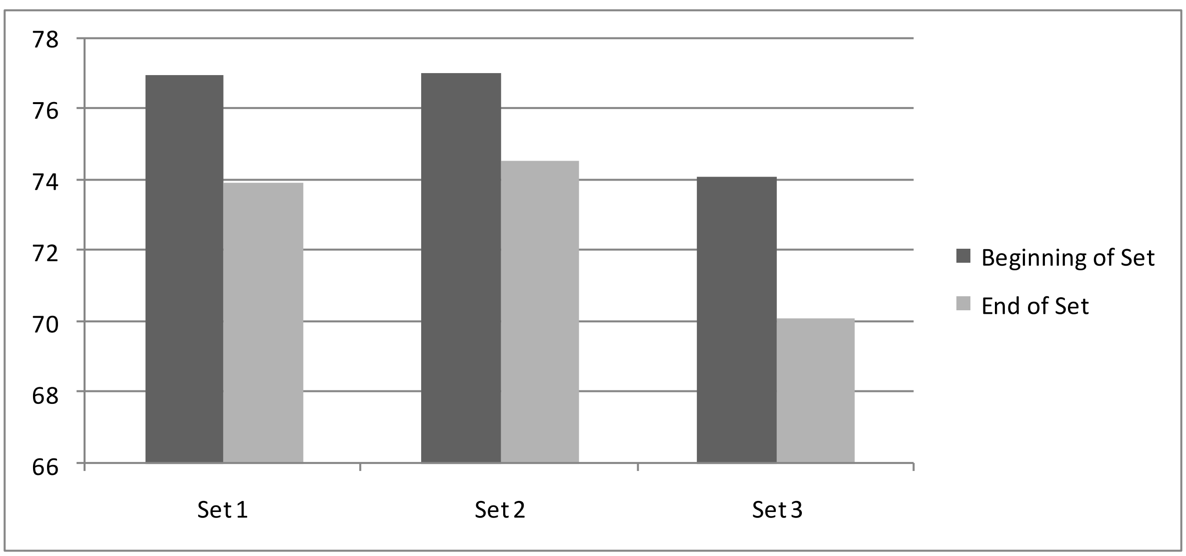

Figure 10. Bar graph of average knee flexion per set. Values are in Degrees(n=10).

Knee angular velocity. No significant differences were seen between sets, $F(2,7) = 0.42$, $p = .662$. No significant differences were seen between tests, $F(1,8) = 1.25$, $p = .292$. Additionally, no significant interaction was seen between the sets and tests, $F(5,4) = 0.44$, $p = .649$. Table 2 gives the mean and standard deviation for all time of measurement for knee angular velocity. Figure 11 shows the trend of the data across all times of measurement.

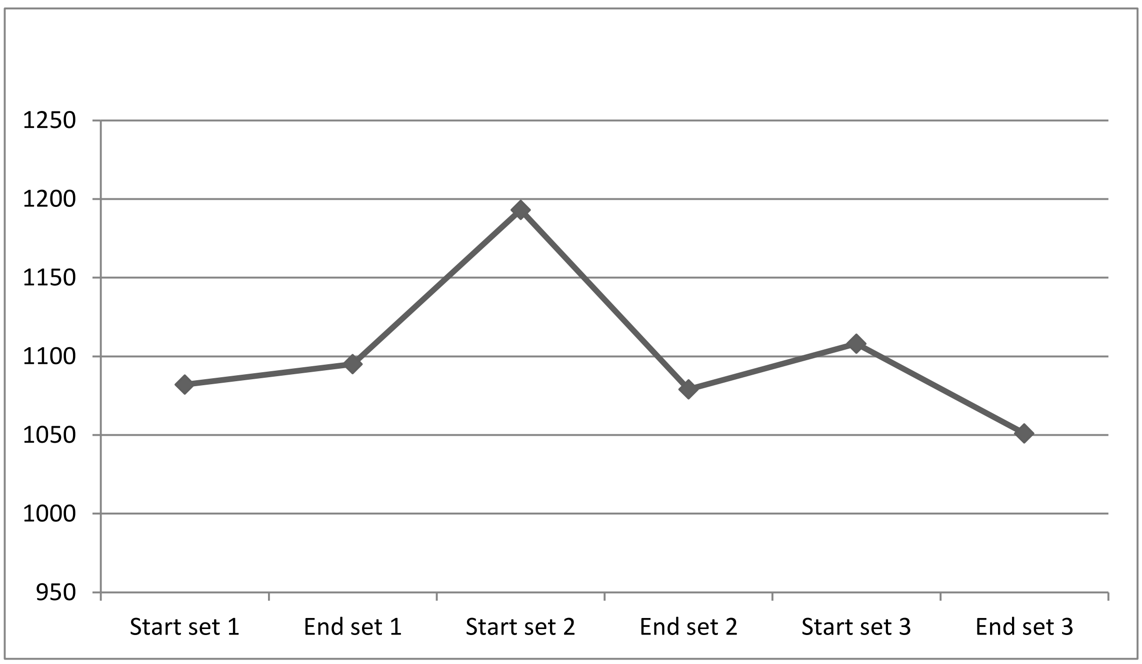

Figure 11. Line graph of average angular velocity. No differences were seen for any of the times of measurement. Values are in degrees per second (n=10).

Knee Angular Velocity

Table 2. Average knee angular velocity for each set and test. Values are in degrees per second (n=10).

	Beginning of Set	End of Set
	Mean ± S.D.	**Mean ± S.D.**
Set 1	1082±479	1095±525
Set 2	1193±523	1080±521
Set 3	1108±462	1052±417

Electromyography

Root mean square: rectus femoris. Significant differences were seen in the *rectus femoris* for the RMS values between sets, F(2,7) = 4.90, p = .02, η^2 = .352 (see Figure 12). The *post hoc* power analysis indicated the sample of 10, with an alpha of .05 and a small effect size provided power of .732. Pairwise comparisons show set one (M = 3.47, SD = 2.45) was greater than both sets two (M = 2.26, SD = 1.84, p = 0.022, d = .53) and three (M = 2.67, SD = 2.10, p = .031, d = .35). No significant differences were seen between tests, F(1,8) = 4.32, p = .067. A significant interaction was seen between the sets and tests F(5,4) = 4.98, p = .019, η^2 = .356. The *post* hoc power analysis indicated the sample of 10, with and alpha of .05 and a small effect size provided power of .740. Table 3 gives the mean and standard deviation for all the times of measurement for the RMS of the *rectus femoris*.

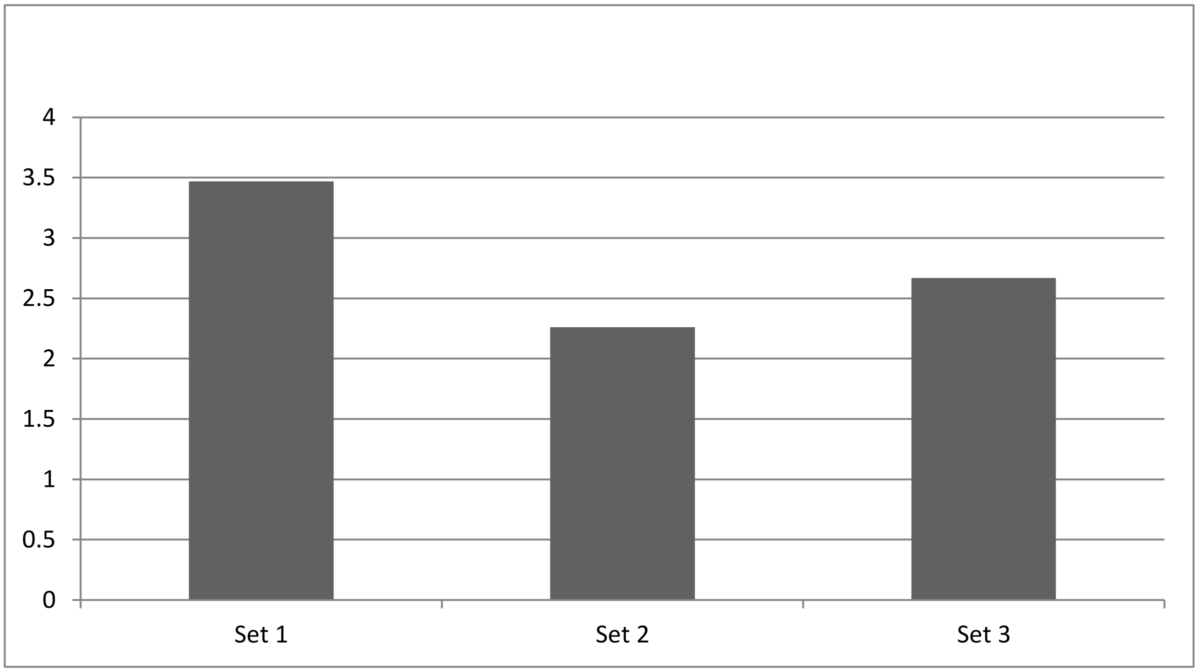

Figure 12. Bar graph of RMS rectus femoris data by set. Values are in volt-seconds (n=10).

RMS Rectus Femoris

Table 3. Average RMS values for rectus femoris for each set and test. Values are in volt-seconds (n=10).

	Beginning of Set	**End of Set**
	Mean ± S.D.	**Mean ± S.D.**
Set 1	4.02±2.43	2.93±2.46
Set 2	2.48±2.11	2.04±1.60
Set 3	2.48±1.80	2.85±2.44

Root mean square: biceps femoris. With regards to the RMS values of the *biceps femoris,* significant differences were seen between sets, F(2,6) = 7.59, p = .017, η^2 = .487 (see Figure 13). The *post* hoc power analysis indicated the sample of 10, with and alpha of .05 and a small effect size provided power of .751. Pairwise comparisons show set one (M = 2.40, SD = 1.81) was greater than both sets two (M = 1.62, SD = 1.51, p = .008, d = .47) and three (M = 1.48, SD = 1.74, p = .026, d = .52). Significant differences were seen between tests, F(1,7) = 17.22, p = .003, η^2 = .683. The *post* hoc power analysis indicated the sample of 9, with an alpha of .05 and a small effect size provided power of .951. The beginning of the set (test one; M = 2.07, SD = 1.82) was greater than the end of the set (test two; M = 1.59, SD = 1.60). Effect size between tests was d = .28. Figure 14 shows that the beginning of each set is always greater than the end of the set. No significant interaction was seen between the sets and tests, F(5,3) = 4.00, p = .072. Table 4 gives the mean and standard deviation for all the times of measurement for the RMS of the *biceps femoris.*

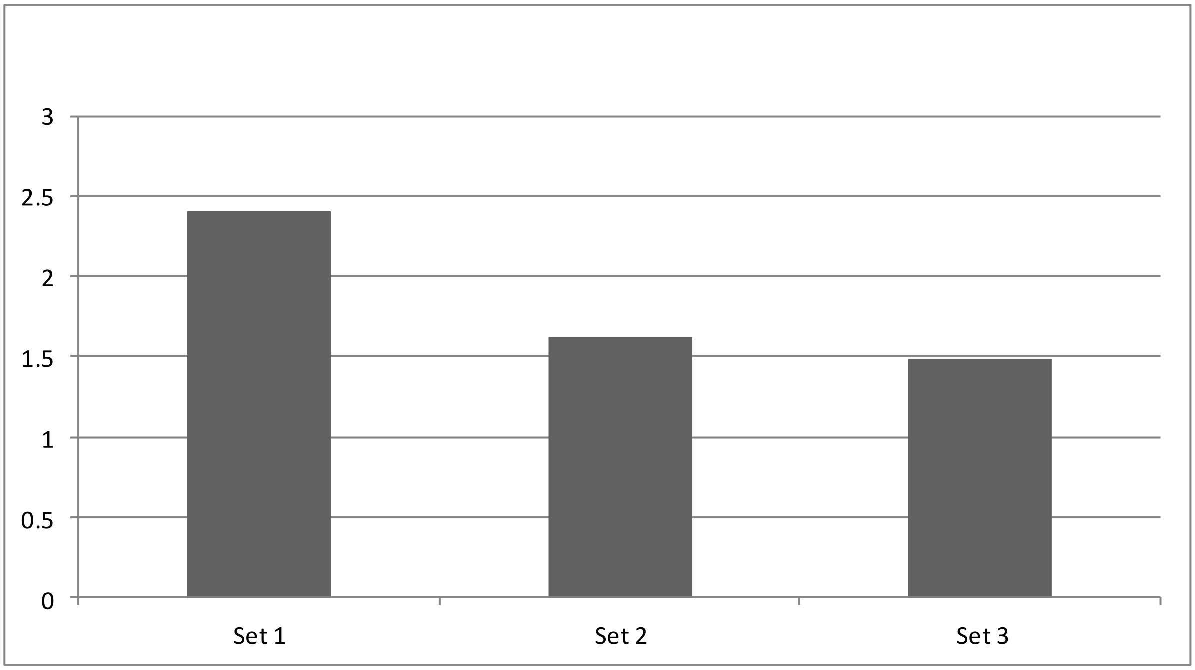

Figure 13. Bar graph of RMS biceps femoris data by set (n=9). Values are in volt-seconds.

RMS Biceps Femoris

Table 4 . Average RMS values for biceps femoris for each set and test. Values are in volt-seconds (n=9).

	Beginning of Set	End of Set
	Mean ± S.D.	**Mean ± S.D.**
Set 1	2.95±1.96	1.86±1.57
Set 2	1.71±1.56	1.52±1.54
Set 3	1.56±1.77	1.39±1.82

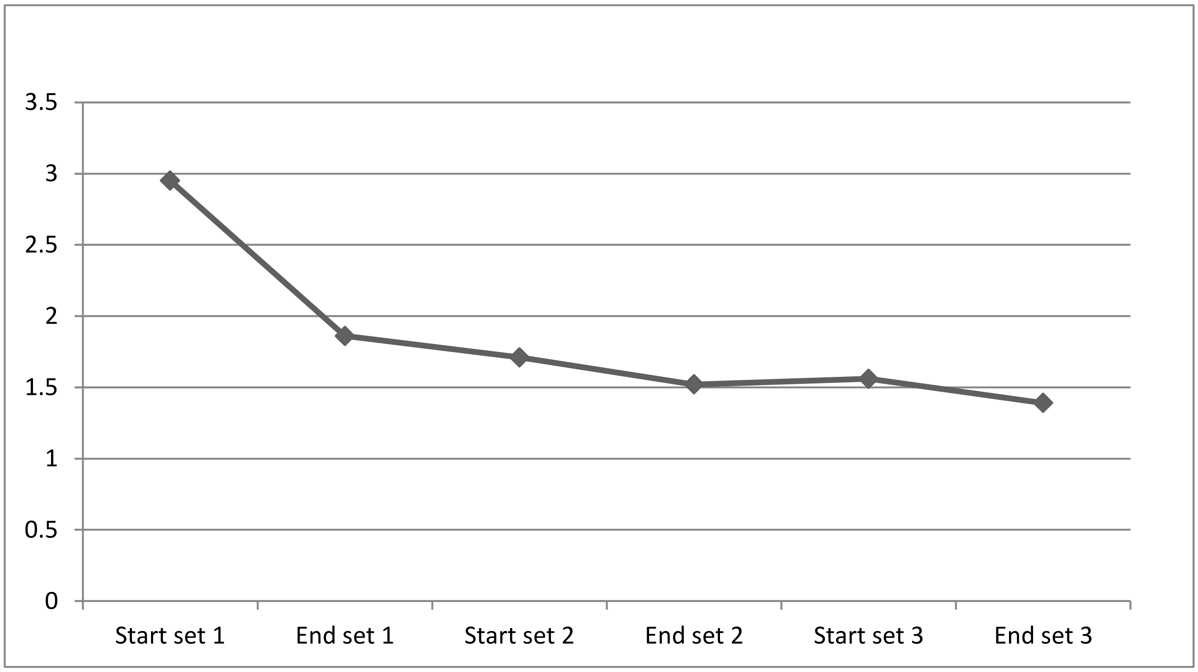

Figure 14. Line graph RMS of biceps femoris data for each set and test. Values are in volt-seconds (n=9).

Median power frequency. With regards to the MPF values of the *biceps femoris*, Significant differences were seen between sets, F(2,6) = 5.27, p = .017, η^2 = .397 (see Figure 15). The *post* hoc power analysis indicated the sample of 10, with and alpha of .05 and a small effect size provided power of .755. Pairwise comparisons show set three (M = 39.34, SD = 20.33) was significantly greater than set one (M = 29.32, SD = 13.79, p = .043, d = .58) and set two (M = 32.45, SD = 16.97, p = .019, d = .37). Figure 16 shows the overall upward trend in the data. No significant differences were seen between tests, F(1,7) = 2.08, p = .187. No significant interaction was seen between the sets and tests, F(5,3) = 1.42, *p* = .27. Table 5 gives the mean and standard deviation for all the times of measurement for the MPF of the *biceps femoris.*

MPF Biceps Femoris

Table 5. Average MPF values for biceps femoris for each time of measurement. Values are in hertz (n=9).

	Beginning of Set	End of Set
	Mean ± S.D.	**Mean ± S.D.**
Set 1	30.26±13.10	28.37±15.76
Set 2	32.39±19.09	32.51±15.74
Set 3	34.17±17.65	44.50±22.52

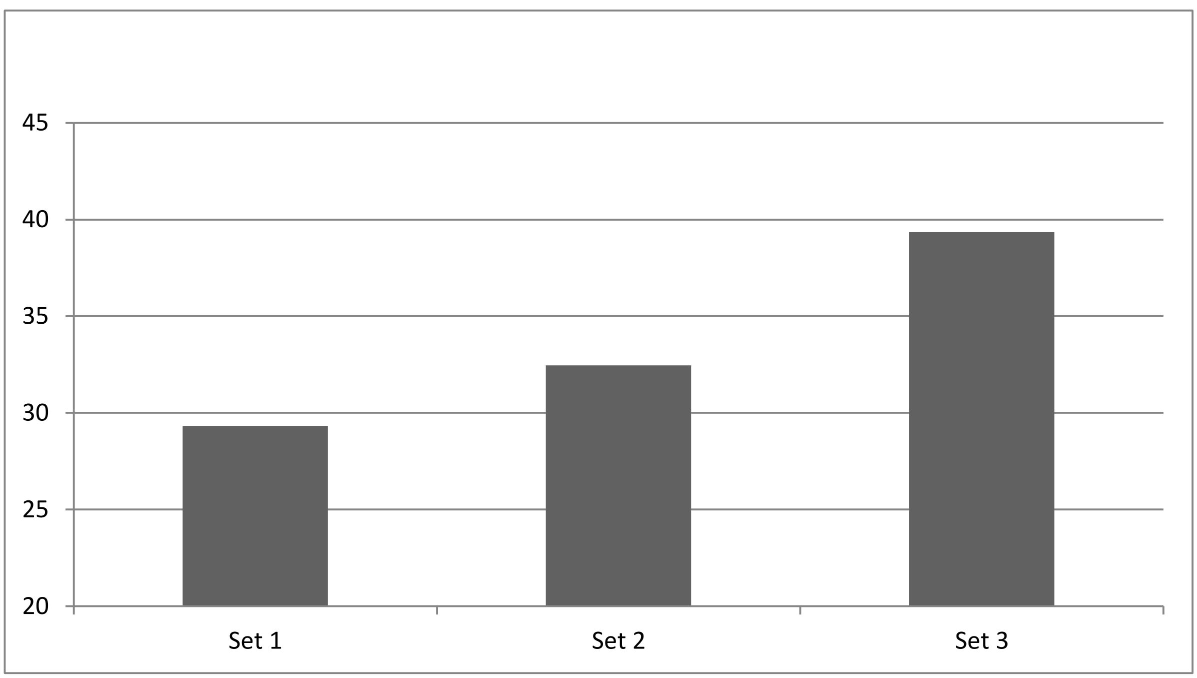

Figure 15. Bar graph of MPF biceps femoris data by set. Values are in hertz (n=9).

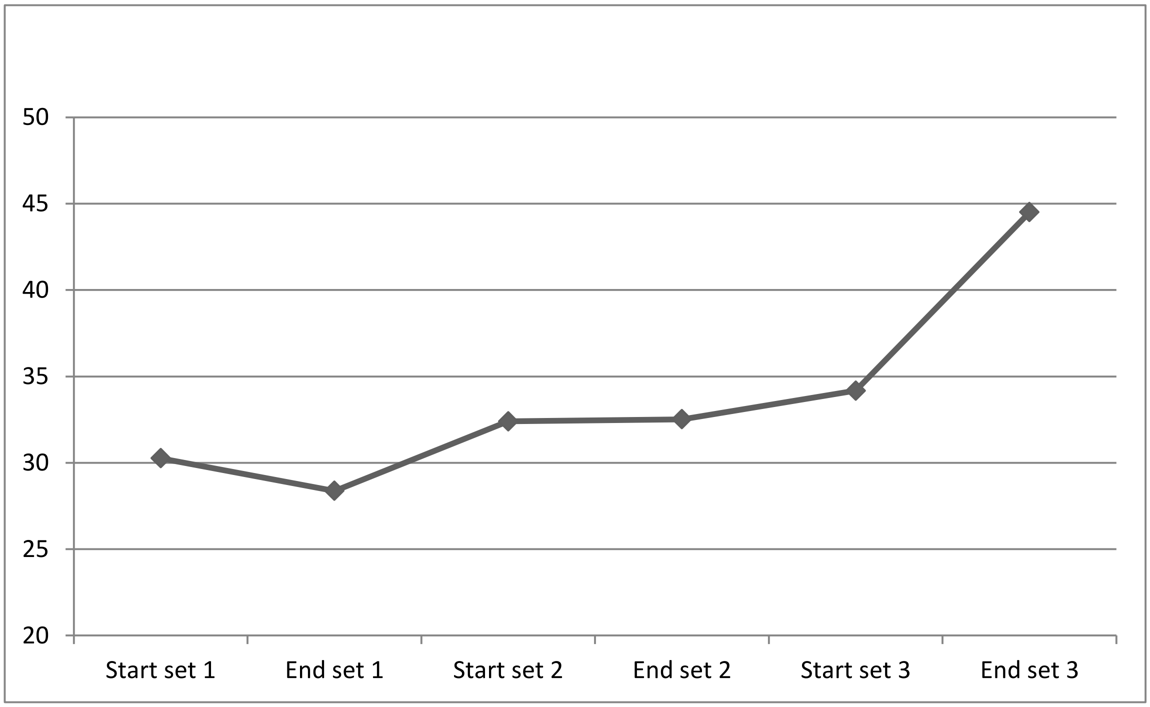

Figure 16. Line graph MPF of biceps femoris data for each set and test. There is a general upward trend in frequency. Values are in hertz (n=9).

Chapter Five

Discussion

Overview

Kinematic data revealed participants experienced less knee flexion at the end of each set compared to the beginning. This indicates a less effective use of the legs and thus a less effective kinetic chain leading to the racket striking the ball. Significant differences in the EMG data show a reduction in root mean square values. The differences seen in the variables tested suggest that as the match progressed the participants experienced a reduction in the effectiveness of their leg drives. This may have negative consequences for the serve such as reduction in velocity and accuracy.

Kinematics

The results showed that during the course of a three-set tennis match several factors are affected with regards to the legs during the serve. The knees were always flexed to a greater extent at the beginning of each set than at the end of the set. This pattern held true for all three sets played. For the first set knee flexion dropped from 76.96º to 73.96º. There is a rebound at the start of the second set to 77.04º which in fact is the highest average recorded for the entire match. Just as it happened in the first set, the average drops down at the end of the second set; this time to an average of 74.57º. It is at this point, the start of the third set, which we see a break in this pattern of the average of the set's beginning increasing over the average of the previous set's end. When the third set begins there is no increase in flexion angle (average 74.11º) over the second set's end. With the final measurement, average flexion angle has continued to decrease and the lowest value is recorded for the entire experiment (70.09º).

The decrease in knee flexion has far reaching consequences on the serve. A decrease in knee flexion indicates a less effective leg drive during that portion of the serve. Flexing the knee less, which indicates using a less effective leg drive, decreases the velocity at which the racket is swung at. This is because as the server drives upward with their legs, the racket is driven downward at its maximum vertical velocity (Elliott, Marsh, & Blanksby, 1986). When the racket is driven more effectively downward in this fashion it has a greater distance to travel in order to strike the ball. This allows for the greatest velocity to be built up before impact. Previous studies done using force plates have splinted the server's legs in order to reduce their knee flexion and found that the serve was significantly affected when compared to a serve under normal conditions (Girard, Micallef, & Millet, 2007). Readings of ground reaction forces show much greater forces present during normal conditions than compared to when the knees were splinted. This greater GRF for the normal serving condition is a result of a forceful leg drive (Girard, Micallef, & Millet, 2007). While in the current study the server's knees were obviously not physically splinted, reducing the amount of flexion through any other mechanism will naturally have the same effect on the serve. There were two other interesting findings that should be noted here by Girard, Micallef, and Millet. Knee flexion before extension is necessary for efficient execution of the serve, and this holds true regardless of performance level. The researchers reached the conclusion that an effective leg drive, if coordinated with appropriate trunk rotations increases the serves efficiency by driving the racket down, behind and away from the back which lengthens the trajectory of the racket to the ball. Second, Girard, Micallef, and Millet, showed that ball impact height and speed were affected by splinting the knee. Ball impact height, as concluded by Elliott, Marsh, and Blanksby, plays a vital role in the margin for error on the serve. Increasing ball impact height serves to increase the margin for error by decreasing the number of balls hit into the net.

There is also a certain plyometric element present in the serve which a reduction in knee flexion will negatively affect. When the server initiates the knee flexion during the serve there is a natural stretch-shortening cycle that stores elastic energy. This elastic energy can only be helpful in assisting the leg drive if flexion is quickly followed by knee extension (Girard, Micallef, & Millet, 2005). The same concept is also applicable to baseball pitchers. They were required to wait an additional .97 seconds between the eccentric and concentric phases of the stretch-shorten cycle movement of internal rotation of the upper arm and ball and wrist velocity were negatively affected (Elliott, Baxter, & Besier, 1999). In order to complete a successful stretch-shortening cycle the working muscles must be stretched to a certain extent before forcefully shortening. If the muscle is stretched too much or too little then there will be little benefit yielded from the cycle. If the reduction in knee flexion seen in the current study were enough to disrupt or curtail the effectiveness of the stretch-shortening cycle, then that would have a detrimental effect on server's ability to rapidly extend toward the ball. The server would either serve with a reduced capacity to hit his most effective serve or try for a compensative measure in some other way. As will be discussed later on, it is usually the latter route that is taken. The amount of time the participants took to change from knee flexion to extension was not recorded during this study. This would be an interesting variable to consider, should a similar study be conducted as well as recording the possible best knee flexion angle for optimum stretch-shortening angles for each subject.

As was shown by the data on knee angular velocity, there was no difference in the angular velocity of the knee across any of the six times of measurement during the current study. The overall average across all times of measurement was 1101± 487 deg/sec which is slightly higher than previous research which showed an average angular velocity of 800± 400 deg/sec (Fleisig, Nicholls, Elliott, & Escamilla, 2003). The lack of any difference across the six times of measurement indicates that while the velocity at which the knees extended stayed the same throughout the match, the physical distance the legs could extend was decreasing throughout the match, thus negatively affecting the serve. This is the same conclusion Elliott, Marsh, and Blanksby reached in 1986. Increasing the trajectory of the racket to the ball will help to increase final racket velocity upon ball impact which is a great benefit to the server.

The decrease seen in knee flexion, coupled with no changes seen in angular velocity, has indications for the amount of work and power done during the serve. Muscular power is the product of net muscle moment and angular velocity at a given joint (Winter, 2009). If we assume that net muscle moment isn't significantly changed, we then would expect overall power to be unchanged, due to the fact that angular velocity is unchanged throughout the match. With a reduction in knee flexion, the distance the joint has to extend is reduced. This results in a lesser amount of time the joint has to output power which results in less work being done. While further study would be needed to verify this conjecture, the ultimate end of this line of reasoning would lead to the conclusion that the quantity of joules produced from the serve has been decreased.

In addition to the myriad of negative effects already discussed, there is another, potentially more harmful, consequence of reductions in knee flexion during the serve throughout the match. Reid, Elliott, and Alderson studied the relationships between lower-limb coordination and shoulder joint kinetics and kinematics during the serve. Participants served under three conditions: using a wide stance, a narrow stance, and minimal lower-limb action, which the researchers called the ARM condition. Racket speed was affected by differential leg drive, but peak anterior force about the shoulder and its rate of development was the same regardless of condition (2008). If force on the shoulder was the same regardless of leg drive, and there is a kinetic chain which builds up force starting with the legs - as stated by Kibler and Van der Meer in 2001 - then this would indicate that another part of the body is compensating for a less useful leg drive. The compensating effect places larger forces on other body parts, which could lead to injury. Reid, Elliott, and Alderson noted that players had more lateral flexion and rotation of their shoulders and trunks during the ARM serve, which was thought to be a compensatory measure for the reduction seen in leg drive (2008). With the legs contributing less to the service motion and the resulting drop in ball impact height, there is a great chance that a large number of second serves will have to be hit as well. Aside from the already detrimental strategic impact of missing a large percentage of first serves, the player must cope with the overall strain placed on the body from hitting even more serves. Chow et al. showed that in professional players the main difference between first and second serves is not in pre-impact racket speed-as many people would believe-but in ball toss location and rack orientation. In fact, pre-impact vertical and lateral velocities are greater in second serves in order to increase the amount of spin imparted to the ball (2003). This means that regardless of what type of serve is hit there is a great deal of stress placed on the resultant body parts, especially if the legs have reduced their contribution to the start of the kinetic chain.

Electromyography

For the EMG data, three different parameters were looked at. First root mean square data was analyzed for both the *rectus femoris* and the *biceps femoris*. Additionally median power frequency was analyzed for the *biceps femoris* only. Significant differences were seen in the RMS data for both muscle groups. There was a difference between sets for both muscles, but the *biceps femoris* also had a test difference as well. There is a downward trend in the data for both muscle groups. Figure 17 shows the *rectus femoris* decreased until the end of the second set and there started a slight climb. The *biceps femoris* continued decreasing throughout the match.

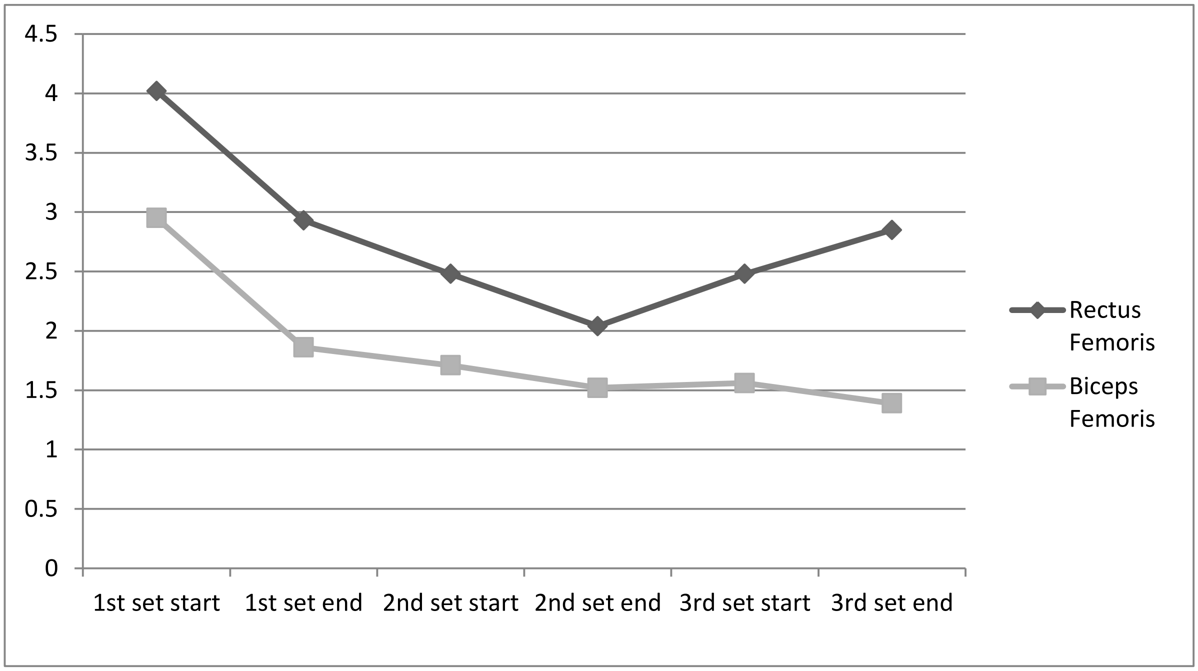

Figure 17. Line graph RMS data of the rectus femoris and biceps femoris. Values are in volt-seconds.

Achieving significant differences between sets was not an unexpected outcome. From the hypothesis it was thought a difference would be seen in the muscle activity after a long three-set tennis match. However, decreases seen in the RMS data (as evidenced by Figure 17) were surprising to the researchers. The downward trend in RMS is actually the opposite of what expected during fatigue contractions. An increase of RMS values is thought to signal fatigue, not a decrease; it must be clarified that most previous knowledge of this is based on isometric contractions, so the effect of repeated dynamic contractions on the EMG signal in an open environment is not especially well known (Criswell, 2011).

Effect of three sets on kinematics and leg muscle activation

Overall the data suggests that subjects experienced an increase in the output of the *biceps* femoris while the *rectus femoris* decreased after the start of the second set. The gain in amplitude (an indicator of fatigue) by the *rectus* femoris never breaks the mark set at the beginning of the first set, so the RMS data shows negligible amounts of fatigue for the *rectus femoris.* While the subjects were obviously experiencing changes in their leg muscles during the serve, what these changes were and what they signal is difficult to tell. Based on the participant’s physical reactions and own observations on their state off tiredness, it would seem they were experiencing a loss and not a gain of muscular output. If it is assumed that the same fatigue patterns hold true for isometric, as well as dynamic contractions, then it would appear that neither muscle experienced any of the conventional indicators of fatigue for RMS.

Adding in the median power frequency data on the *biceps femoris* yields few answers to the present question. The third set MPF was greater than the first and second sets and Figure 16 (Chapter 4) shows upward trend in the data over the course of the match. Knowledge of MPF is widespread in dealing with isometric contractions. During isometric contractions, as the muscle becomes more fatigued, MPF is seen to decrease as a profusion of hydrogen ions slows down the waveform of the muscle contraction (Criswell, 2011). From this we see that, just like the RMS values, the increase in frequency for the *biceps femoris* is the opposite of what is thought should happen. One previous research study done on dynamic muscular contractions had participants complete knee extension sets to failure with 15 reps per set. It was found that, just as in isometric studies, the RMS values were increasing while MPF values were decreasing (Mileva, Morgan, & Bowtell, 2009). In the current study, both muscles experienced the opposite of what was expected. Three possible, contributing factors to the current findings are posited by Farina in *Interpretation of the Surface Electromyogram in Dynamic Contractions*. In dealing with dynamic contractions there are marked differences when compared to the more customary isometric contractions. First, is signal nonstationarity, meaning signal properties can changes at much faster rates due to rapid recruitment and derecruitment of motor units and changes in joint angle. Second, although electrodes positioning was standard throughout the test, a change in joint angle can result in the electrode to shift position with regards to the muscle fibers, thus resulting in a different position at each instant during the movement. The shift in electrodes causes an unwanted component of the signal that is extremely difficult to predict, or for that matter, remove. Finally, tissue conductivity changes when angular displacement about a joint causes changes in length, diameter, and orientation of the muscle fiber (Farina, 2006). All three of the above stated problems with dynamic contractions are present in the serve and could be a few of the leading reasons for the perplexing results for the EMG analysis.

As stated earlier, the *biceps femoris* was shown to continue its downward trend in RMS even when its antagonist was leveling off. Also the increase in MPF indicates a greater output from the *biceps femoris*. There is another possible explanation for the observations seen in the *biceps femoris*, aside from the one's already postulated by Farina. The greatest amount of work done during the serve occurs after full knee flexion, when the legs and hips powerfully extend upwards toward to ball. This upward phase of the serve requires more work than the downward phase of the serve, and it is the *rectus femoris,* along with the other quadriceps muscles, that is responsible for the powerful knee extension necessary for an effective serve. The *biceps femoris* plays a vital role in flexing the knee, which is also an action necessary for an effective serve to take place. However, unlike the role of the knee extensors in the serve, the flexors have the force of gravity on their side. Players could help in facilitating flexion by simply allowing gravity to do most of the work and using their muscles as a stop mechanism for the movement rather than facilitators. If this is true, then it would help explain why after three sets there were no large indicators of fatigue for the *biceps femoris*,

The above postulation presents one troubling problem since it would seem logical to conclude that if bending the knees comes at little metabolic cost to the *biceps* femoris, then flexion angles should not be decreasing at the end of each set. A slider-crank mechanism model (Figure 18) may help in alleviating this problem. In the figure, the top block represents the body, the bottom block represents the ankle, and the middle joint represents the knee. As flexion angles decrease, the moment arm between the knee and line of gravity also decreases which means that the torque the quadriceps need to generate in order to lift and accelerate the body is also small. The opposite is also true, as flexion angles increase, the quadriceps must increase the amount of torque produced. The decrease in flexion means the *rectus femoris* did not have to produce as much torque in order to lift the body which could help explain the RMS findings.

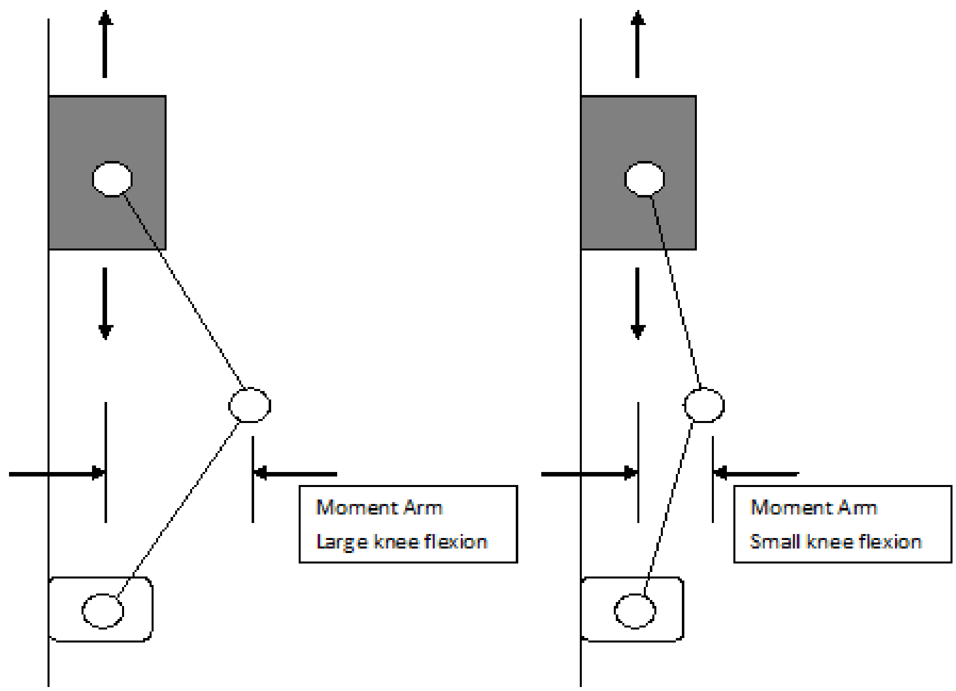

Figure 18. Slider-crank mechanism model.

Examining past research done on tennis using EMG helps little in yielding conclusions to the present study. Many of the studies that conducted EMG as part of the experiment did not deal with fatigue or match like settings. They instead were dealing with timing patterns of muscles, such as Girard, Micallef, and Millet in 2005, or Chow, Park, and Tillman in 2009. The former study looked at muscle activation patterns between beginner, intermediate, and expert groups of servers while the latter examined trunk muscle activation patterns for different types of serves. The studies done to look at the effect fatigue has on tennis dealt to a much greater extent with outcomes such as shot accuracy and velocity. For instance, Vergauwen, Brounds, and Hespel conducted an interesting study that assessed the effect carbohydrate supplementation had on tennis performance, but all evaluations were done based on things such as error rate and ball velocity (1998). There were no kinematic, kinetic, or EMG recordings taken so the underlying mechanisms for this outcome are unknown. These constraints were discussed earlier in Chapter 1, and the problems presented by these studies still remain. There is little to compare the current results with in order to ascertain if the overall EMG pattern seen for the two muscles in question is a common occurrence or a one-time phenomenon not to be repeated again. Additional study of muscle EMG activity during the serve is necessary to unlock the answers to these key questions.

Limitations

The current study was conducted in an open, outdoor environment and thus has more limitation than would otherwise be present in a controlled laboratory. The decision was made to have subjects play an actual match instead of a simulated fatigue test, because the researchers wanted results that were very applicable to real world conditions. This uncontrolled environment could have played a role in the great variability seen between the participants. It should be noted that this study was conducted during December, when the average temperature over the test days was 14.4ºC (58ºF). Many participants commented afterwards on their depreciated physical state following the conclusion of the matches played. If this study was conducted during the month of July, when the average temperature in Tyler, Texas is above 34ºC (93ºF), then the results could potentially yield much greater differences across all parameters. The effects of exercising in the heat are well known, and singles tennis play during high temperatures contributes greatly to increases in skin temperature and perceived levels of thermal discomfort from players (Morante & Brotherhood, 2007).

There are several problems that arise with conducting this study in the heat instead of the December cool, the biggest being with the recording equipment necessary for the study. During one of the experimental matches, one of the wireless EMG amplifiers overheated as a result of being in the sun for too long. This would present a real problem for the summer months, since even in the shade the temperature can be quite high. Also the electrodes used for recording of muscle activity might need to be altered in some way to allow for the fact that many players experience excessive sweating during play in the heat. This could lead to great changes in the conductivity of the skin over the course of the match and facilitate the electrodes becoming detached altogether. During the current study this occurrence was rare but it still had to be dealt with on a small scale. If during seemingly cool temperatures the subjects sweated enough to cause the electrodes to slip, then it takes little imagination to envision the problems that would be encountered when moving the study to the summer.

One final limitation that should be addressed with future research is the sample rate of the EMG system. For recording the muscle activity during the serve, the EMG was set to a recording frequency of 1,000 hertz. The serve is obviously a very quick movement and the researchers recommend increasing the frequency gain in order to ensure accurate readings of the entire service motion.

Practical Applications and Future Research

The researchers wanted the study to be very applicable to real work tennis matches. Playing in an uncontrolled environment could have decreased the power of the study, but results that did return significant differences have great implications for those directly involved in the sport of tennis. Players and coaches can use the knowledge pertaining to knee flexion in order to make better informed decisions with regards to the serve during the course of a tennis match. If the player is experiencing a deficiency in serving, especially during the latter stages of each set, then the player and the coaches could use the knowledge of knee flexion reduction to make corrections to the serve. This will also help coaches when teaching the serve to place the proper amount of emphasis on the legs during the serve. In doing this, coaches can help their pupils to gain the proper serve motion that is required for a proficient serve and make sure no undue stress in placed on specific body parts.

Observant readers will no doubt notice that although there were significant differences in flexion angles and also in the EMG data, these changes don’t readily appear to be very great. The greatest difference in knee flexion between any of the times of measurement was seven degrees which occurred between the beginning of the second set and the end of the third set. However, this should not be taken to mean that subtle differences in biomechanics do not translate to marked differences in real world outcomes. A small difference of a few inches can mean the difference between hitting a high percentage of first serves in and missing in the net. Future research in this area should investigate the outcome of a decrease in knee flexion on ball impact height. It was noted earlier that as ball impact height decreases, the number of serves missed (especially in the net) increases. If a future study could show that even a small decrease in flexion causes an increase in the number of errors due to ball impact height, then the benefits of focusing on the legs would be enormous.

Few studies done on tennis combine the practicality of real world matches with hard scientific parameters, such as kinematics and electromyography. It is in the practical applications that sports science can help players and coaches to the greatest extent. It is obvious we still have a great deal to learn about tennis, both in the easily observable stroke parameters, such as accuracy consistency, and also in the underlying mechanisms responsible for everything we see. Perhaps tennis legend Vic Braden put it best when he said, “In many way we are still in the Stone Age in understanding how to maximize performance in young players…The good news is that more and more scientists are getting into the field of biomechanics and eventually, there will be a serious and joint scientific effort to solve today’s tennis challenges” (Braden, 2008 p.43). It is the researchers’ hope that this study will have contributed to the knowledge of the game and allowed for the advancement of the underlying fundamentals of the game.

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Appendices

Appendix A: IRB and Informed Consent

Institutional Review Board Research Application

THE UNIVERSITY OF TEXAS AT TYLER
INSTITUTIONAL REVIEW BOARD

EXPEDITED RESEARCH APPLICATION

IRB: *F2011-29*

Approved by: *G. Duke*

Date: *11-16-11*

To qualify for expedited review research must present no more than minimal risk to human subjects and cannot explore sensitive topics. In addition the research must fit the categories of expedited research, per OHRP regulations.

Attach (electronically) with this application:

- Written consent form unless a waiver of written informed consent is requested
- Dean/Department Chair Approval (to be sent by Dean or Department Chair electronically)
- Brief research proposal that outlines background and significance, research design, research questions/hypotheses, data collection instruments and related information, data collection procedures, data analysis procedures.
- Human Subject Education Certification for PI, co-investigators, and research assistants participating in recruitment, data collection, data analysis, or, if they have any exposure to identifiable data (if training has not been completed at UT Tyler within a 3 year period of time)

Appendix A continued

- Tool/instrument/survey; if copyright or other issues prohibit electronic form, submit one hard copy

DATE:

Principal Investigator	*Fenter* (Last)	*Brad* (First)	*A* (MI)
PI Title and Credentials	☐ Assistant Professor ☐ Professor		☐ Associate Professor ☒ Other
Faculty Sponsor/Telephone *(if PI is student)*	*Dr. Neil Dong/(903) 565-5615*		
PI's Department	*Health & Kinesology*		
PI's Telephone Number	*(940) 357-9206*		
Contact Person in Absence of PI	*Dr. Neil Dong*		
Telephone #s	*(903) 565-5615*		
Title of Proposed Research (must match the NIH/Sponsor title if applicable)	*The Effect of a Three Set Tennis Match on Knee Kinematics and Quadriceps Activation During the Tennis Serve*		
Start Date/Finish Date	*11/14/11 to 04/30/12*		
Source of Funding	☐ NIH ☐ Local ☐ Industry ☐ Other Federal (Specify) ☒ Other (Specify) Health & Kinesiology Dept., UT Tyler		

COMPLETE <u>ALL</u> ITEMS TO AVOID DELAY IN IRB APPROVAL

1. Designate the category that qualifies this proposal for expedited review (see UT Tyler Expedited Categories at the end of this application) and justify this designation by responding to the statements below each category

Category # *7* Information Required for Justification (See specific information under each category)

2. If this is a retrospective chart review (Category 5)(health records research), refer to the IRB's HIPAA policies and procedures and complete any appropriate forms. In addition, all of the following **must be addressed**: 1) describe specifically what data will be collected, whether or not subject identifiers will be present, and at what point in time identifiers will be destroyed. 2) state why the research could not practicably be carried out without access to and use of the protected health information.

3. **Purpose Of Study:** *Determine the effect a three set match has on knee kinematics and quadriceps activation during the serve of collegiate male tennis players.*

4. **Research Questions:** *Do three set tennis matches cause a reduction in the use of the legs during the tennis serve?*

5. **Background and Significance of Study (may copy/paste from proposal but please include just enough to demonstrate significance):**

One of the most important aspects of tennis is the serve. Those who possess good serves are at a great advantage over those who do not. At the collegiate level, and above, having a good serve is of the upmost importance. The legs play a vital role in the serve as they are the beginning of the kinetic chain that culminates in striking a successful serve. However, playing multiple sets of tennis can be a very fatiguing process. If playing a long match induces enough physiological strain in the muscles, then the quality of the serve is thought to go down. It is believed among most tennis players that the legs are the cause of this decrease in serve efficiency, but no study currently exists to corroborate or refute this thinking. In this study, it is thought that knee kinematics (flexion, angular velocity, angular acceleration) and quadriceps activation will be negatively affected as fatigue increases with each set played.

6. **POPULATION AND SAMPLE**

6a. Inclusion and exclusion criteria: *Individual males that play or have played for the University of Texas at Tyler are included. Those that do not play tennis for UT Tyler are excluded. Females that play for the university have been excluded to control for any confounding factors that might have been introduced by having both genders participate in the study.*

General Inclusion:

- Approximate number of subjects *12* ☐ NA
- Age Range *18-25*
- Gender: Males ☒ Yes ☐ No Females ☐ Yes ☒ No
  Explain below if either gender is excluded.
  Females have been excluded to control for any confounding factors that might be introduced by having both genders participate in the study.
- Will all racial/ethnic groups be included? ☐ No ☒ Yes ☐ NA
  Explain any exclusion.

Protocol Sample Inclusion Criteria: *Participants must play or have played tennis as a collegiate athlete*

Protocol Sample Exclusion Criteria: *Those that have not played tennis as a collegiate athlete. Additionally Females have been excluded to insure a homogeneous sample group.*

6b. Special classes possibly eligible to participate in the research: ☐ Mentally Impaired
☐ Children ☐ Pregnant Women

Note: *Studies with the following class* <u>*cannot*</u> *be Expedited:* ***Prisoners***

6c. **Recruitment procedures** (attach any recruitment materials, e.g., flyers, advertisements, telephone script, letters, etc.
Emails sent with the permission of the head tennis coach of the prospective players.

6d. **Method of Sampling (convenience, etc.):** *Convenience*

6e. **Method of Sample Recruitment and Persons Responsible for Recruitment**:

Methods of sample recruitment include emails and invites sent to collegiate tennis teams Members in PI Group are responsible for recruitment.

7. **Informed Consent**

Describe the method to be used to obtain informed consent. Prospective research ordinarily requires written informed consent. If any special classes are eligible to participate, discuss how the consent process will differ. **Inclusion of children (under 18 years) requires permission of at least one parent AND the assent of the child (refer to UT Tyler's Policy on Informed Consent of Children)**. *Please see attached form titled "Informed Consent"*

For sample participants under the age of 18 years, the PI is responsible for abiding by the UT Tyler Policy on Informed Consent for Children.

7a. **This section only for those requesting a waiver or alteration of informed consent**

Justify the waiver or alteration in accordance with the following four criteria established under 45CFR46.116(d)(1-4). All four criteria must be met.

1. The research involves no more than minimal risk* to the subjects ☐ Yes ☐No
2. The waiver or alteration will not adversely affect the rights and welfare of the subjects
☐ Yes ☐No
3. The research could not practicably be carried out without the waiver or alteration,
☐Yes ☐ No AND
4. Whenever appropriate, the subjects will be provided with additional pertinent information after participation ☐ Yes ☐ No.

8. **Data Collection Procedures** (specify who, what, when, where, how, duration type of information) *Who: Data collection will be done by Brad Fenter and Dr. Dong on current and former members of the UT Tyler Tennis Team*

What: Three sets of tennis where knee kinematics and quadriceps activation are examined.

When: 11/14/11 till 04/30/12;

Where: UT Tyler Tennis Courts

How: First, participants will arrive at the time specified for sample statistics such as weight, and age. Once on the court the participants will engage in a standard 10 minute tennis warm-up. Markers will be placed *on the participants hip, knee and ankle of the back serving leg. High speed video cameras will be placed at the back fence on both sides of the court perpendicular to the baseline. The cameras will be used to digitize the serves for kinematic analysis. A wireless electromyography module will be attached to the leg to monitor muscle activation during the serve. Once this is complete, the participants will play a three set match. The first and last five serves struck each set will be measured for a total of 6 different times of measurement.*

Duration: Three sets will be played lasting at least 9 games total or 35 minutes each.

9. **Confidentiality of Data:** Specify how confidentiality will be maintained for research data and/or specimens.
   Please refer to the "Informed Consent", section: "Confidentiality and Privacy Protections".

10. **Identifiability of data or specimens**: Will the specimens or data be identifiable?

   ☒ Yes ☐ No If yes, complete item 9a

   9a. State the type of identification, direct or indirect, on any specimens or data when they are made available to your study team: *Subjects will be given a number to identify them (i.e. the first subject will be given number 1 and so on). While filming, the subject's face will be identifiable. If a photograph is used in a figure by the investigators, then the face of the subject will be blacked out*

   Direct Identifiers include subject name, address, social security, etc.

   Indirect Identifiers include any number that could be used by the investigator or the source providing the data/specimens to identify a subject, e.g., pathology tracking number, medical record number, sequential or random code number)

11. **Access to Data**: Specify faculty and staff (members of the study team) permitted to have access to the study data.
   PI Group (Brad Fenter & Dr. Neil Dong)

12. **Protection of Data:** **State** how data will be protected, e.g., located filing cabinet in investigator's office, on password protected computer, location(s) of computer, etc.
   Password protected computer. The video taken during the study will be stored in Dr. Dong's office after the investigation is completed.

13. **<u>Risks and benefits to the subjects and/or society</u>**

<u>Risks</u>: *Playing multiple sets of tennis could lead to soreness, muscle cramping, and exhaustion.*

<u>Benefits</u>: *A definitive answer to the whether the legs drop out of the kinetic chain during multiple sets of tennis could have significant implications for coaching tennis.*

SIGNATURE OF PRINCIPAL INVESTIGATOR: Signature indicates agreement by the PI to abide by UT Tyler IRB policies and procedures in the UT Tyler Handbook and the Federal Wide Assurance, to the obligations as stated in the "Responsibilities of the Principal Investigator" and to use universal precautions with potential exposure to specimens.

Brad Fenter	*11/3/11*
Principal Investigator Signature (Electronic submission of this form by PI indicates signature)	Date

IRB Approval

The University of Texas at Tyler
Institutional Review Board

November 16, 2011

Dear Mr. Fenter,

Your request to conduct the study entitled *The Effect of a Three Set Tennis Match on Knee Kinematics and Quadriceps Activation During the Tennis Serve* is approved as an expedited study, IRB #F2011-29 by The University of Texas at Tyler Institutional Review Board. This approval includes the use of the written informed consent that is attached to this approval letter. Please use this attached form for all persons, and ensure that each participant is able to repeat the purpose of the study, the voluntary nature of it, any risks involved, and who to contact other than you as the PI. In addition, ensure that any research assistants or co-investigators have completed human protection training, and have forwarded their certificates to the IRB office (G. Duke).

Please review the UT Tyler IRB Principal Investigator Responsibilities, and acknowledge your understanding of these responsibilities and the following through return of this email to the IRB Chair within one week after receipt of this approval letter:

- This approval is for one year, as of the date of the approval letter
- Request for Continuing Review must be completed for projects extending past one year
- Prompt reporting to the UT Tyler IRB of any proposed changes to this research activity
- Prompt reporting to the UT Tyler IRB and academic department administration will be done of any unanticipated problems involving risks to subjects or others
- Suspension or termination of approval may be done if there is evidence of any serious or continuing noncompliance with Federal Regulations or any aberrations in original proposal.
- Any change in proposal procedures must be promptly reported to the IRB prior to implementing any changes except when necessary to eliminate apparent immediate hazards to the subject.

Best of luck in your research, and do not hesitate to contact me if you need any further assistance.

Appendix A continued

Sincerely,

Gloria Duke, PhD, RN

Gloria Duke, PhD, RN
Chair, UT Tyler IRB

Informed Consent

THE UNIVERSITY OF TEXAS AT TYLER
Informed Consent to Participate in Research

Institutional Review Board #F2011-29
Approval Date: 11-16-11

1. **Project Title**: **The Effect of a Three Set Tennis Match on Knee Kinematics and Quadriceps Activation During the Tennis Serve**

2. **Principal Investigator: Brad Fenter**

3. **Participant's Name:**

To the Participant:

You are being asked to take part in this study at The University of Texas at Tyler (UT Tyler). This consent form explains why this research study is being performed and what your role will be if you choose to participate. This form also describes the possible risks connected with being in this study. After reviewing this information with the person responsible for your enrollment, you should be able to understand and make an informed decision on whether you want to take part in this study.

4. Description Of Project

The purpose of this study is to ascertain the effect multiple sets of tennis have on the legs. Specifically, a device called an electromyography module will be fitted to the quadriceps muscles. This device will provide the researchers with information such as the amount of muscle activation during the serve. A high speed video camera will be used to digitize the serving motion during the match through the placement of anatomical markers on the hip, knee, and ankle. This information will help in understanding the effects of playing on proper form while serving. You will be asked to play 3 sets of tennis just as you would during a normal match. Regardless of the outcome of the first and second set and third set will be played.

5. Research Procedures

If you agree to be in this study, we will ask you to do the following things:

- You will wear clothing that allows for ease of placement of electrodes and anatomical markers without disrobing in any way (spandex or Under

Armour type clothing will work best).

- You will conduct a standard ten minute warm-up.
- Electrodes will be placed on you quadriceps muscles and anatomical markers will be placed on you hip, knee, and ankle
- You will play three sets of tennis with each set lasting at least 35 minutes or 9 games.
- As a consequence of filming the serve, your face will be recognizable to those analyzing the video. Photographs used from the study in any future paper or publication will not include any recognizable facial features.
- All data from this study will be kept on password encoded computers that are not accessible to those outside the investigators.

6. Side Effects/Risks

Soreness, muscle cramps, and exhaustion are all possible side effects associated with participation in this study. In addition, allergic reactions to alcohol swabs may be experienced when placing electrodes. In the event of illness such as that due to exhaustion, you will be referred to the campus health clinic or to your on personal physician at your own expense if you wish.

7. Potential Benefits

A better knowledge of the processes that occur in the serve as a direct result of playing three sets which could lead to greater understanding for both players and coaches the role fatigue plays in the serve.

<u>Understanding Of Participants</u>

8. I have been given an opportunity to ask any questions concerning this research study and the researcher has been willing to answer my questions.

9. If I sign this consent form I know it means that:

- I am taking part in this study because I want to. I chose to take part in this study after having been told about the study and how it will affect me.
- I know that I am free to not participate in this study and that if I choose to not participate, then nothing will happen to me as a consequence.
- I know that I have been told that if I choose to participate, then I can stop being a part of this study at any time. I know that if I do stop being a part of the study, then nothing will happen to me.

- I will be told about any new information that may affect my willingness to continue participating in this study.

- The study may be changed or stopped at any time by the researcher or by The University of Texas at Tyler.

- The researcher will gain my written consent for any changes that may affect me.

10. I have been assured that that my name will not be revealed in any reports or publications resulting from this study without my expressed written consent.

11. I also understand that any information collected during this study, including any health-related information, may be shared with the following as long as no identifying information as to my name, address, or other contact information is provided):

- Organization contributing money to be able to conduct this study
- Other researchers interested in combining your information with information from other studies
- Information shared through presentations or publications

12. I understand The UT Tyler Institutional Review Board (the group that ensures that research is done correctly and that measures are in place to protect the safety of research participants) may review documents that have my identifying information on them as part of their compliance and monitoring process. I also understand that any personal information revealed during this process will be kept strictly confidential.

13. I have been told of and I understand any possible expected risks that are associated with my participation in this research project.

14. I also understand that I will not be compensated for any patents or discoveries that may result from my participation in this research.

15. If I have any questions concerning my participation in this project, I shall contact the principal researcher: **Brad Fenter, 940-357-9206, bfenter@patriots.uttyler.edu**

17. If I have any questions concerning my rights as a research subject, I shall contact Dr. Gloria Duke, Chair of the IRB, at (903) 566-7023, gduke@uttyler.edu,
or the University's Office of Sponsored Research:

The University of Texas at Tyler

c/o Office of Sponsored Research
3900 University Blvd
Tyler, TX 75799

I understand that I may contact Dr. Duke with questions about research-related injuries.

18. <u>CONSENT/PERMISSION FOR PARTICIPATION IN THIS RESEARCH STUDY</u>

Based upon the above, I consent to taking part in this study as it is described to me. I give the study researcher permission to enroll me in this study. I have received a signed copy of this consent form.

Signature of Participant Date

Signature of Person Responsible (e.g., legal guardian) Relationship to Participant

Witness to Signature

19. I have discussed this project with the participant, using language that is understandable and appropriate. I believe that I have fully informed this participant of the nature of this study and its possible benefits and risks. I believe the participant understood this explanation.

Researcher/Principal Investigator Date

Appendix B: Statistical Data Tables

Knee Flexion

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
set	.896	.877	2	.645	.906	1.000	.500
Test	1.000	.000	0	.	1.000	1.000	1.000
set * Test	.897	.868	2	.648	.907	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept

Within Subjects Design: set + Test + set * Test

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Paramet	Observed Power[a]
Set	Sphericity Assumed	166.734	2	83.367	2.270	.132	.201	4.540	.401
	Greenhouse-Geisser	166.734	1.812	92.019	2.270	.138	.201	.4113	.378
	Huynh-Feldt	166.734	2.000	83.367	2.270	.132	.201	4.540	.401
	Lower-bound	166.734	1.000	166.734	2.270	.166	.201	2.270	.271
Error(set)	Sphericity Assumed	661.051	18	36.725					
	Greenhouse-Geisser	661.051	16.308	40.536					
	Huynh-Feldt	661.051	18.000	36.725					
	Lower-bound	661.051	9.000	73.450					
Test	Sphericity Assumed	150.575	1	150.575	9.197	.014	.505	9.197	.770
	Greenhouse-Geisser	150.575	1.000	150.575	9.197	.014	.505	9.197	.770
	Huynh-Feldt	150.575	1.000	150.575	9.197	.014	.505	9.197	.770
	Lower-bound	150.575	1.000	150.575	9.197	.014	.505	9.197	.770
Error(Test)	Sphericity Assumed	147.345	9	16.372					
	Greenhouse-Geisser	147.345	9.000	16.372					
	Huynh-Feldt	147.345	9.000	16.372					
	Lower-bound	147.345	9.000	16.372					
set*test	Sphericity Assumed	6.196	2	3.098	.253	.780	.027	.505	.084
	Greenhouse-Geisser	6.196	1.813	3.417	.253	.780	.027	.505	.084
	Huynh-Feldt	6.196	2.000	3.098	.253	.780	.027	.505	.084
	Lower-bound	6.196	1.000	6.196	.253	.780	.027	.505	.084
Error (set*test)	Sphericity Assumed	220.831	18	12.268					
	Greenhouse-Geisser	220.831	16.321	13.531					
	Huynh-Feldt	220.831	18.000	12.268					
	Lower-bound	220.831	9.000	24.537					

a. Computed using alpha = .05

Estimated Marginal Means

1. Grand Mean

Measure:MEASURE_1

Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
74.450	4.059	65.268	83.633

Sets

Estimates

Measure:MEASURE_1

set	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	75.447	4.224	65.891	85.002
2	75.803	4.269	66.146	85.460
3	72.102	4.127	62.765	81.439

Pairwise Comparisons Between Sets

(I)set	(J)set	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	-.356	2.200	1.000	-6.811	6.098
	3	3.345	1.802	.289	-1.942	8.631
2	1	.356	2.200	1.00	-6.098	6.811
	3	3.701	1.711	.176	-1.319	8.721
3	1	-3.345	1.802	.289	-8.631	1.942
	2	-3.701	1.711	.176	-8.721	1.319

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Tests

Estimates

Measure:MEASURE_1

Test	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	76.035	3.919	67.170	84.899
2	72.866	4.259	63.231	82.502

Pairwise Comparisons Between Tests

(I)test	(J)test	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	3.168*	1.045	.014	.805	5.532
2	1	-3.168*	1.045	.014	-5.532	-.805

Based on estimated marginal means
*. The mean difference is significant at the .05 level
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Set * Test

Measure:MEASURE_1

set	Test	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	76.958	3.553	68.921	84.995
	2	73.935	5.076	62.452	85.418
2	1	77.035	4.149	67.649	86.421
	2	74.571	4.424	64.563	84.579
3	1	74.111	4.492	63.949	84.273
	2	70.093	3.866	61.348	78.838

Knee Angular Velocity

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
set	.819	1.593	2	.451	.847	1.000	.500
Test	1.000	.000	0	.	1.000	1.000	1.000
set * Test	.842	1.379	2	.502	.863	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept
Within Subjects Design: set + Test + set * Test

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power [a]
Set	Sphericity Assumed	37097.687	2	18548.844	.423	.662	.045	.846	.108
	Greenhouse-Geisser	37097.687	1.694	21897.038	.423	.630	.045	.716	.103
	Huynh-Feldt	37097.687	2.000	18548.844	.423	.662	.045	.846	.108
	Lower-bound	37097.687	1.000	37097.687	.423	.532	.045	.423	.090
Error(set)	Sphericity Assumed	789659.709	18	43869.984					
	Greenhouse-Geisser	789659.709	15.248	51788.820					
	Huynh-Feldt	789659.709	18.000	43869.984					
	Lower-bound	789659.709	9.000	87739.968					
Test	Sphericity Assumed	41109.582	1	41109.582	1.254	.292	.122	1.254	.171
	Greenhouse-Geisser	41109.582	1.000	41109.582	1.254	.292	.122	1.254	.171
	Huynh-Feldt	41109.582	1.000	41109.582	1.254	.292	.122	1.254	.171
	Lower-bound	41109.582	1.000	41109.582	1.254	.292	.122	1.254	.171
Error(Test)	Sphericity Assumed	295012.021	9	32779.113					
	Greenhouse-Geisser	295012.021	9.000	32779.113					
	Huynh-Feldt	295012.021	9.000	32779.113					
	Lower-bound	295012.021	9.000	32779.113					

a. computed using alpha - .05

Continued on next page

Tests of Within-Subjects Effects continued

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
set*test	Sphericity Assumed	40017.781	2	20008.890	.442	.649	.047	.885	.111
	Greenhouse-Geisser	40017.781	1.727	23176.498	.442	.622	.047	.764	.106
	Huynh-Feldt	40017.781	2.000	20008.890	.442	.649	.047	.885	.111
	Lower-bound	40017.781	1.000	40017.781	.442	.523	.047	.442	.092
Error (set*test)	Sphericity Assumed	814207.153	18	45233.731					
	Greenhouse-Geisser	814207.153	15.540	52394.683					
	Huynh-Feldt	814207.153	18.000	45233.731					
	Lower-bound	814207.153	9.000	90467.461					

a. computed using alpha =.05

Estimated Marginal Means

1. Grand Mean

Measure:MEASURE_1

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
1101.757	142.864	778.576	1424.939

Sets

Estimates

Measure:MEASURE_1

set	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1088.727	144.843	761.069	1416.386
2	1136.558	160.846	772.700	1500.417
3	1079.986	136.992	770.089	1389.882

Pairwise Comparisons Between Sets

(I)set	(J)set	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-47.831	66.139	.488	-197.447	101.785
	3	8.742	77.508	.913	-166.593	184.077
2	1	47.831	66.139	.488	-101.785	197.447
	3	56.572	52.718	.311	-62.685	175.830
3	1	-8.742	77.508	.913	-184.077	166.593
	2	-56.572	52.718	.311	-175.830	62.685

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Tests

Estimates

Measure:MEASURE_1

Test	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1127.933	142.210	806.232	1449.633
2	1075.582	147.274	742.426	1408.738

Pairwise Comparisons Between Tests

(I)test	(J)test	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	52.351	46.747	.292	-53.398	158.100
2	1	-52.351	46.747	.292	-158.100	53.398

Based on estimated marginal means
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Set*Test

Measure:MEASURE_1

set	Test	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	1082.193	151.517	739.438	1424.949
	2	1095.262	165.866	720.048	1470.476
2	1	1193.160	165.328	819.162	1567.158
	2	1079.957	164.632	707.532	1452.381
3	1	1108.445	146.067	778.018	1438.872

Root Mean Square *Rectus Femoris*

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
set	.871	1.108	2	.575	.885	1.000	.500
Test	1.000	.000	0	.	1.000	1.000	1.000
set * Test	.872	1.100	2	.577	.886	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept

Within Subjects Design: set + Test + set * Test

Appendix B continued

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Paramet	Observed Power[a]
Set	Sphericity Assumed	15.205	2	7.602	4.899	.020	.352	9.797	.732
	Greenhouse-Geisser	15.205	1.771	8.586	4.899	.025	.352	8.675	.690
	Huynh-Feldt	15.205	2.000	7.602	4.899	.020	.352	9.797	.732
	Lower-bound	15.205	1.000	15.205	4.899	.054	.352	4.899	.506
Error(set)	Sphericity Assumed	27.935	18	1.552					
	Greenhouse-Geisser	27.935	15.938	1.753					
	Huynh-Feldt	27.935	18.000	1.552					
	Lower-bound	27.935	9.000	3.104					
Test	Sphericity Assumed	2.224	1	2.224	4.323	.067	.324	4.323	.459
	Greenhouse-Geisser	2.224	1.000	2.224	4.323	.067	.324	4.323	.459
	Huynh-Feldt	2.224	1.000	2.224	4.323	.067	.324	4.323	.459
	Lower-bound	2.224	1.000	2.224	4.323	.067	.324	4.323	.459
Error(Test)	Sphericity Assumed	4.630	9	.514					
	Greenhouse-Geisser	4.630	9.000	.514					
	Huynh-Feldt	4.630	9.000	.514					
	Lower-bound	4.630	9.000	.514					
set*test	Sphericity Assumed	5.416	2	2.708	4.979	.019	.356	9.958	.740
	Greenhouse-Geisser	5.416	1.772	3.056	4.979	.024	.356	8.824	.698
	Huynh-Feldt	5.416	2.000	2.708	4.979	.019	.356	9.958	.740
	Lower-bound	5.416	1.000	5.416	4.979	.053	.356	4.979	.513
Error (set*test)	Sphericity Assumed	9.790	18	.544					
	Greenhouse-Geisser	9.790	15.951	.614					
	Huynh-Feldt	9.790	18.000	.544					
	Lower-bound	9.790	9.000	1.088					

a. Computed using alpha = .05

Estimated Marginal Means

1. Grand Mean

Measure:MEASURE_1

Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
2.799	.625	1.384	4.213

Sets

Estimates

Measure:MEASURE_1

set	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	3.471	.757	1.760	5.183
2	2.260	.573	.964	3.556
3	2.665	.654	1.185	4.145

Pairwise Comparisons Between Sets

(I)set	(J)set	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	1.211*	.437	.022	.222	2.201
	3	.806*	.317	.031	.090	1.522
2	1	-1.211*	.437	.022	-2.201	-.222
	3	-.405	.417	.357	-1.349	.538
3	1	-.806*	.317	.031	-1.522	-.090
	2	.405	.417	.357	-.538	1.349

Based on estimated marginal means
*. The mean difference is significant at the .05 level
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Appendix B continued

Tests

Estimates

Measure:MEASURE_1

Test	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.991	.624	1.579	4.404
2	2.606	.640	1.159	4.054

Pairwise Comparisons Between Tests

(I)test	(J)test	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.385	.185	.067	-.034	.804
2	1	-.385	.185	.067	-.804	.034

Based on estimated marginal means
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Set *Test

Measure:MEASURE_1

set	Test	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	4.017	.769	2.276	5.757
	2	2.926	.778	1.166	4.685
2	1	2.481	.667	.972	3.990
	2	2.039	.506	.894	3.184
3	1	2.476	.569	1.190	3.763
	2	2.854	.772	1.108	4.600

Root Mean Square *Biceps Femoris*

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
set	.392	6.557	2	.038	.622	.680	.500
Test	1.000	.000	0	.	1.000	1.000	1.000
set * Test	.289	8.692	2	.013	.584	.624	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept

Within Subjects Design: set + Test + set * Test

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Paramet	Observed Power [a]
Set	Sphericity Assumed	9.052	2	4.526	7.594	.005	.487	15.188	.896
	Greenhouse-Geisser	9.052	1.244	7.278	7.594	.017	.487	9.445	.751
	Huynh-Feldt	9.052	1.361	6.652	7.594	.014	.487	10.334	.782
	Lower-bound	9.052	1.000	9.052	7.594	.025	.487	7.594	.676
Error(set)	Sphericity Assumed	9.535	16	.596					
	Greenhouse-Geisser	9.535	9.950	.958					
	Huynh-Feldt	9.535	10.886	.876					
	Lower-bound	9.535	8.000	1.192					
Test	Sphericity Assumed	3.166	1	3.166	17.220	.003	.683	17.220	.951
	Greenhouse-Geisser	3.166	1.000	3.166	17.220	.003	.683	17.220	.951
	Huynh-Feldt	3.166	1.000	3.166	17.220	.003	.683	17.220	.951
	Lower-bound	3.166	1.000	3.166	17.220	.003	.683	17.220	.951
Error(Test)	Sphericity Assumed	1.471	8	.184					
	Greenhouse-Geisser	1.471	8.000	.184					
	Huynh-Feldt	1.471	8.000	.184					
	Lower-bound	1.471	8.000	.184					
set*test	Sphericity Assumed	2.459	2	1.229	3.988	.039	.333	7.976	.627
	Greenhouse-Geisser	2.459	1.169	2.104	3.988	.072	.333	4.661	.460
	Huynh-Feldt	2.459	1.247	1.972	3.988	.068	.333	4.974	.478
	Lower-bound	2.459	1.000	2.459	3.988	.081	.333	3.988	.420
Error (set*test)	Sphericity Assumed	4.933	16	.308					
	Greenhouse-Geisser	4.933	9.351	.528					
	Huynh-Feldt	4.933	9.977	.494					
	Lower-bound	4.933	8.000	.617					

a. Computed using alpha = .05

Estimated Marginal Means

1. Grand Mean

Measure:MEASURE_1

Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1.830	.537	.591	3.069

Sets

Estimates

Measure:MEASURE_1

set	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	2.404	.557	1.120	3.687
2	1.612	.516	.423	2.801
3	1.475	.597	.098	2.852

Pairwise Comparisons Between Sets

(I)set	(J)set	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	.792*	.226	.008	.272	1.312
	3	.929*	.341	.026	.141	1.716
2	1	-.792*	.226	.008	-1.312	-.272
	3	.137	.177	.461	-.270	.544
3	1	-.929*	.341	.026	-1.716	-.141
	2	-.137	.177	.461	-.544	.270

Based on estimated marginal means
*. The mean difference is significant at the .05 level
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Tests

Estimates

Measure:MEASURE_1

Test	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.072	.539	.830	3.314
2	1.588	.542	.338	2.838

Pairwise Comparisons Between Tests

(I)test	(J)test	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.484*	.117	.003	.215	.753
2	1	-.484*	.117	.003	-.753	-.215

Based on estimated marginal means
*. The mean difference is significant at the .05 level
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Set*Test

Measure:MEASURE_1

set	Test	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	2.948	.653	1.441	4.454
	2	1.860	.523	.653	3.067
2	1	1.708	.521	.506	2.910
	2	1.516	.515	.328	2.703
3	1	1.561	.589	.202	2.921
	2	1.388	.607	-.011	2.788

Median Power Frequency *Biceps Femoris*

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
set	.453	5.546	2	.062	.646	.718	.500
Test	1.000	.000	0	.	1.000	1.000	1.000
set * Test	.398	6.450	2	.040	.624	.684	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept

Within Subjects Design: set + Test + set * Test

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Set	Sphericity Assumed	945.878	2	472.939	5.266	.017	.397	10.533	.755
	Greenhouse-Geisser	945.878	1.293	731.720	5.266	.037	.397	6.808	.605
	Huynh-Feldt	945.878	1.436	658.526	5.266	.032	.397	7.565	.640
	Lower-bound	945.878	1.000	945.878	5.266	.051	.397	5.266	.523
Error(set)	Sphericity Assumed	1436.828	16	89.802					
	Greenhouse-Geisser	1436.828	10.341	138.939					
	Huynh-Feldt	1436.828	11.491	125.041					
	Lower-bound	1436.828	8.000	179.604					
Test	Sphericity Assumed	109.938	1	109.938	2.079	.187	.206	2.079	.247
	Greenhouse-Geisser	109.938	1.000	109.938	2.079	.187	.206	2.079	.247
	Huynh-Feldt	109.938	1.000	109.938	2.079	.187	.206	2.079	.247
	Lower-bound	109.938	1.000	109.938	2.079	.187	.206	2.079	.247
Error(Test)	Sphericity Assumed	423.061	8	52.883					
	Greenhouse-Geisser	423.061	8.000	52.883					
	Huynh-Feldt	423.061	8.000	52.883					
	Lower-bound	423.061	8.000	52.883					
set*test	Sphericity Assumed	386.269	2	193.134	1.423	.270	.151	2.845	.260
	Greenhouse-Geisser	386.269	1.248	309.413	1.423	.271	.151	1.776	.204
	Huynh-Feldt	386.269	1.368	282.381	1.423	.271	.151	1.946	.213
	Lower-bound	386.269	1.000	386.269	1.423	.267	.151	1.423	.184

a. computed using alpha = .05

Continued on next page

Appendix B continued

Tests of Within-Subjects Effects continued

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Paramet	Observed Power [a]
Error (set*test)	Sphericity Assumed	2172.232	16	135.765					
	Greenhouse-Geisser	2172.232	9.987	217.503					
	Huynh-Feldt	2172.232	10.943	198.501					
	Lower-bound	2172.232	8.000	271.529					

Estimated Marginal Means

1. Grand Mean

Measure:MEASURE_1

Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
33.704	4.960	22.266	45.141

Sets

Estimates

Measure:MEASURE_1

set	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	29.318	4.292	19.420	39.216
2	32.454	4.879	21.204	43.705
3	39.339	6.447	24.473	54.205

Appendix B continued

Pairwise Comparisons Between Sets

(I)set	(J)set	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-3.136	2.667	.273	-9.286	3.014
	3	-10.021*	4.159	.043	-19.613	-.429
2	1	3.136	2.667	.273	-3.014	9.286
	3	-6.884*	2.350	.019	-12.302	-1.466
3	1	10.021*	4.159	.043	.429	19.613
	2	6.884*	2.350	.019	1.466	12.302

Based on estimated marginal means
*. The mean difference is significant at the .05 level
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Tests

Estimates

Measure:MEASURE_1

Test	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	32.277	4.912	20.949	43.605
2	35.130	5.199	23.141	47.120

Pairwise Comparisons Between Tests

(I)test	(J)test	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-2.854	1.979	.187	-7.418	1.710
2	1	2.854	1.979	.187	-1.710	7.418

Based on estimated marginal means
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Appendix B continued

Set *Test

Measure:MEASURE_1

set	Test	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	30.262	4.365	20.196	40.329
	2	28.373	5.059	16.708	40.039
2	1	32.394	6.364	17.718	47.069
	2	32.515	5.247	20.415	44.614
3	1	34.174	5.882	20.611	47.738
	2	44.503	7.506	27.194	61.812